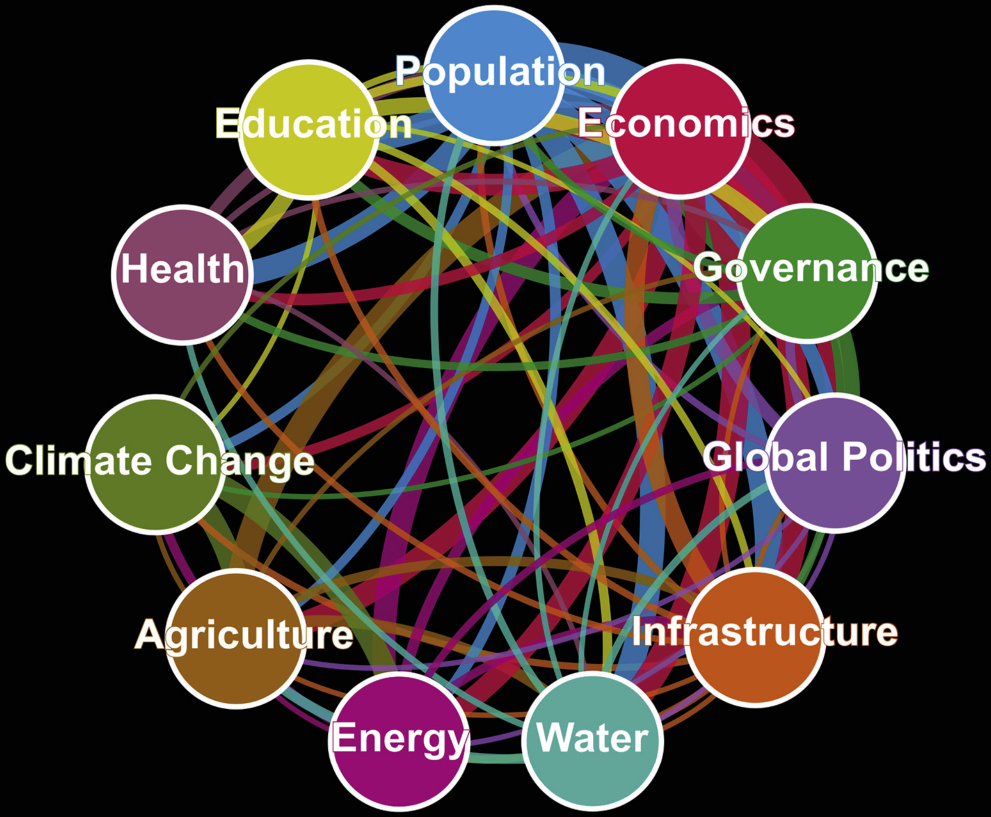

INTERNATIONAL FUTURES

Building and Using Global Models

BARRY B. HUGHES

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Prologue

It is now half a century since the emergence of the first computer models for thinking about possible long-term global futures and for considering how we might, in at least some small way, make those futures better. This volume surveys and reports on the field of global modeling, including early world models and more recent integrated assessment models. In the process of that review, considering strengths, weaknesses, and possible future directions, the book gives special attention to a modeling project that I have led, namely that around the International Futures (IFs) system. At least some parts of the volume should be of interest to a wide range of those thinking seriously about global change: students and scholars, policy analysts (and ideally decision makers), concerned citizens, and, of course, global modelers.

I have had the great privilege of studying and developing such models over that entire half-century period. My first exposure to the audacious idea of building long-term multiissue global computer simulations began in 1972 at Case Western Reserve University. The work underway at MIT on a model called World3 (building on World1, arguably the first such global model) inspired a group of us at Case Western Reserve under the leadership of Mihajlo (Mike) Mesarovic to build the World Integrated Model (WIM), adding regional and model detail to World3's fairly simple representation of the world as a whole.

Several other teams developed world models, as they were then called, in that first decade, and it was a heady period for those of us involved in the effort. I was very much aware, however, of the dangers of overselling our ability to understand global change and to contribute with confidence to policy discussions. Further, while very concerned about the large and growing pressure that humans place on the environment, I was not convinced of the seeming inevitability of global collapse produced by almost all model runs of World3 by the MIT group, as reported in their book *The Limits to Growth*, popularized by the Club of Rome.

At the end of the 1970s I embarked on the project of creating a new world model called International Futures. My goal was an educational tool, especially for university students, but also for helping policy analysts think about the future. The acronym IFs intentionally conveys both the uncertainty of our understanding of possible futures and the reality that any story or scenario about the future from a model is essentially a complex if-then statement—we humans are creating the future by our choices, whether or not we can fully understand their impact.

At the same time, an entirely new stream of global modeling was emerging. It was tied in part to the energy shocks of the global economy in the 1970s, but quickly directed a large portion of its attention to climate change. Under its umbrella label of integrated assessment models (IAMs), the assorted projects also focused on other human impacts upon biophysical systems including land use, biodiversity loss, air pollution, and water system stress. Although motivated by policy-related issues and initiatives, not least the work of the Intergovernmental Panel on

Climate Change, the IAM projects retained close connections to the scientific world.

While IFs grew from the early world modeling tradition, it is very much now an IAM as well, based at the University of Denver's Frederick S. Pardee Center for International Futures since the Center's establishment in 2009. Given the background of IFs, however, it has more focus than other IAMs on issues of human development such as poverty and hunger reduction, advance of education, and improvement of health. That has positioned it well for a new era marked by the enunciation of the Sustainable Development Goals (and before that the Millennium Development Goals) and the related global effort to improve the human condition in an environmentally sustainable world.

As this historical survey of the development of IFs and global modeling indicates, IFs development and this volume owe very much to far more people than I can possibly acknowledge and thank. My apologies to so very, very many who have supported the effort over time and are not named. Among those I must mention are earlier co-authors and long-time friends, Evan Hillebrand, Jakkie Cilliers, and Richard Chadwick. Also, Jonathan Moyer, current director of the Pardee Center, continues strongly to support making IFs a living and evolving tool for anyone wishing to add to its development or use. Institutionally, the University of Denver and the Josef Korbel School of International Studies have been wonderful professional homes for IFs and for me. Most especially, the ongoing development of IFs at the university's Pardee Center would not have been possible without the generous support of Frederick Pardee.

Many more from the IFs and broader global modeling communities have given help in the preparation of this volume. Steve Hedden, Brian O'Neill, Dale Rothman, Dominique van der Mensbrugghe, and Heleen van Soest provided feedback on the broad manuscript during at least one stage of its evolution. Theodore (Ted) Gordon, Håvard Hegre, Mohammod Irfan, Peter Johnston, Samir KC, Elmar Kriegler, Randall Kuhn, Paul Lucas, Wolfgang Lutz, Patrick McCully, Adrian Pop, Paul Raskin, Mark Rosegrant, José Solorzano, and Jin Zhouying reacted very usefully to some portions of it. Elizabeth Bremer led graphic production, while David Bohl and Alanna Markle provided support. Kanishka Narayan managed data updates steadily throughout. Most especially, Janet Dickson, my wife and professional colleague, knows this volume as well as I do and contributed in a wide variety of ways. Of tremendous importance was a constant flow of ideas for improvement, ranging from overall structure to specific conceptualizations and to clarity and details of presentation. She combined all that with consistently positive and strong support in an enterprise that often seemed almost hopelessly ambitious. Further, she undertook bibliographic support, digging deeply into wide-ranging literatures; did the most careful of reading and editing; and provided reactions to my writing when it went astray. If you do find the volume helpful to you in any way, these people, and especially Janet, deserve your thanks as well as mine.

Glossary I: Model Acronyms and Abbreviations

AGE	applied general equilibrium model
AIM	Asia-Pacific Integrated Model
AOGCMs	atmosphere-ocean general circulation models
CGE	computable general equilibrium model
CROPWAT	Crop water and irrigation requirements tool; no elaborated name
DICE	Dynamic Integrated model of Climate and the Economy
DNE21	Dynamic New Earth 21
DSSAT	Decision Support System for Agrotechnology Transfer
ENV-Growth	Environment and economic growth model; no elaborated name
ENVISAGE	Environmental Impact and Sustainability Applied General Equilibrium model
ENV-Linkages	A dynamic general equilibrium model; no elaborated name
EPIC	Environmental Policy Integrated Climate model
ESMs	earth system models
EUGene	Expected Utility Generation and Data Management Program
FAIR	Finite Amplitude Impulse Response model (six linked modules)
FeliX	Functional Enviro-economic Linkages Integrated neXus
FUGI	Future of Global Interdependence
FUND	Climate Framework for Uncertainty, Negotiation, and Distribution
G4M	Global Forest Model
GAEZ	Global Agro-Ecological Zones system
GAINS	Greenhouse gas—Air pollution Interactions and Synergies
GCAM	Global Change Assessment Model
GCMs	global climate models
GEM	Global Economic Model
GEM-E3	General Equilibrium Model for Economy-Energy-Environment
GINFORS	Global Interindustry FORecasting System
GISMO	Global Integrated Sustainability MOdel
GLOBIO	Global Biodiversity model
GLOBIO-Aquatic	Extension of GLOBIO; human impacts on freshwater biodiversity
GLOBIOM	Global Biosphere Management Model
GLOBUS	World model; no elaborated name
GLOFRIS	Global Flood Risk with IMAGE Scenarios
H08	Global hydrology model; no elaborated name

IAMs	integrated assessment models
IFs	International Futures model system
IGSM	Integrated Global System Model
IMACLIM	Simplified climate model/no elaborated name found
IMAGE	Integrated Model to Assess the Global Environment
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
iPETs	integrated Population-Economy-Technology-Science system
LEITAP	Landbouw Economisch Instituut Trade Analysis Project
LINKAGE	General equilibrium model; no elaborated name
LPJmL	Lund-Potsdam Jena managed Land model
MACRO	General economic model; no elaborated name found
MaGE	Macroeconometrics of the Global Economy
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MAGNET	Modular Applied GeNeral Equilibrium Tool
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MAMS	Maquette for MDG Simulations
MERGE-ETL	Model for Evaluating Regional and Global Effects of greenhouse gas reduction policies
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MOIRA	Model of International Relations in Agriculture
PAGE	Policy Analysis of the Greenhouse Effect
PCR-GLOBWB	PCRaster GLOBal Water Balance model
PHOENIX	Population and health model; no elaborated name
POLES	Prospective Outlook on Long-term Energy Systems
PoleStar	World model; no elaborated name
REMIND	Regional Model of Investments and Development
RICE	Regional Integrated model of Climate and the Economy
SARUM	Systems Analysis Research Unit Model
SIMLINK	Developing world trade and growth model; no elaborated name
SIMPEST	Simulating Political, Economic, and Strategic Interactions Among Major Powers
T21	Threshold 21
TARGETS	Tool to Assess Regional and Global Environmental and health Targets for Sustainability
TIAM	TIMES Integrated Assessment Model
TIMER	Targets IMage Energy Regional model
USLE	Universal Soil Loss Equation
WaterGAP	Water—Global Analysis and Prognosis model
WEFM	World Economy Forecasting Model
WEM	World Energy Model
WIM	World Integrated Model
WITCH	World Induced Technical Change Hybrid model
World3	World model; no elaborated name
WorldScan	World model; no elaborated name

Glossary II: Modeling-Related Concepts, Tools, and Databases

AQUASTAT	Food and Agriculture Organization's global water information system
BBOE	billion barrels of oil equivalent
CBR	crude birth rate
CDR	crude death rate
COPDAB	Conflict and Peace Data Bank
DALYs	disability-adjusted life years
DataGator	Pardee Center data analysis tool
EDGAR	Emissions Database for Global Atmospheric Research
EJ	exajoules
FAOSTAT	Food and Agriculture Organization database
FBIC	formal bilateral influence capacity index
GAMS	General Algebraic Modeling System
GEMPACK	General Equilibrium Modeling PACKage
GPI	global power index
GUI	graphical user interface
HDI	Human Development Index
ISCED	International Standard Classification of Education
KEDS	Kansas Event Data System
LES	linear expenditure system
MFP	multifactor productivity
MID	Militarized Interstate Disputes dataset
PAFs	population attributable fractions
PID controller	equilibrium system controller (Proportional to Integral and Derivative)
Ppm	parts per million
RR	relative risk
SAM	social accounting matrix
SCC	social costs of carbon dioxide emissions
SNA	System of National Accounts
TFP	total factor productivity

TFR	total fertility rate
VVA	verification, validation, and accreditation
WDI	World Development Indicators
YLDs	years of living with a disability
YLLs	years of life lost

Glossary III: Organizations, Projects, and Teams

ADVANCE	Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies
AgMIP	Agricultural Model Intercomparison and Improvement Project
AMIP	Atmospheric Model Intercomparison Project
AMPERE	Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
BGR	Federal Institute for Geosciences and Natural Resources (Germany)
CD-LINKS	linking Climate and Development policies-Leveraging International Networks and Knowledge Sharing
CEPII	Research Center in International Economics (France)
CEPLAN	National Center for Strategic Planning (Peru)
CMIP	Coupled Model Intercomparison Project
COW	Correlates of War project
CPB	Netherlands Bureau for Economic Policy Analysis
CRA	Comparative Risk Assessment project
DFID	Department for International Development (United Kingdom)
EMF	Energy Modeling Forum
FAO	Food and Agriculture Organization of the United Nations
FP7	7th Framework Programme for European Research and Technological Development
GBD	Global Burden of Disease project
GEA	Global Energy Assessment project
GEO	Global Environment Outlook project
GHE	Global Health Estimates
GSG	Global Scenario Group
GTAP	Global Trade and Analysis Project
IAMC	Integrated Assessment Modeling Consortium
ICTD	International Centre for Tax and Development
IEA	International Energy Agency
IGO	intergovernmental organization
IHME	Institute for Health Metrics and Evaluation
IIASA	International Institute for Applied Systems Analysis

IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ISS	Institute for Security Studies (pan-African)
LIMITS	Low climate IMpact scenarios and the Implications of required Tight emission control Strategies
MDGs	Millennium Development Goals
MEA	Millennium Ecosystem Assessment project
MILES	Modelling and Informing Low Emission Strategies
NDCs	Nationally Determined Contributions to emissions control
NIC	National Intelligence Council (United States)
OECD	Organisation for Economic Co-operation and Development
PBL	Netherlands Environmental Assessment Agency
PIAMDDI	Program on Integrated Assessment Model Development, Diagnostics, and Intercomparison
PIK	Potsdam Institute for Climate Impact Research
PITF	Political Instability Task Force
PRIO	Peace Research Institute Oslo
PwC	PricewaterhouseCoopers
RCPs	Representative Concentration Pathways
RoSE	Roadmaps toward Sustainable Energy futures project
ScenarioMIP	Scenario Model Intercomparison Project
SDGs	Sustainable Development Goals
SIPRI	Stockholm International Peace Research Institute
SRES	Special Report on Emission Scenarios
SSPs	Shared Socioeconomic Pathways
TWI2050	The World in 2050
UCDP	Uppsala Conflict Data Program
UNCCD	United Nations Convention to Combat Desertification
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNPD	United Nations Population Division
WATCH	Water and Global Change integrated project
WaterMIP	Water Model Intercomparison Project
WFaS	Water Futures and Solutions initiative
WHO	World Health Organization
WIC	Wittgenstein Centre for Demography and Global Human Capital

CHAPTER 1

Introduction

The global community has clear goals for improving the human condition.[1] Eliminate poverty and hunger. Provide quality education and health care to all. Strengthen governance that functions inclusively, protects security, and delivers public goods effectively. Advance and spread economic wellbeing while protecting our biological and physical environments across the generations.

The choices and actions of individuals, groups, organizations, and countries will shape the character and rate of progress of this long-term project. We do not all, however, share the same mental models of global dynamics and the probable reactions of systems to these choices and actions. Computer simulations rooted in large-scale databases are codifications of such understandings. These databases and simulations, in the form of global models, can facilitate the conversations that are needed to share our own mental models of global change and to learn from those of others.

Such global models can contribute much to collective advance in exploring and shaping better futures. Modeling projects generally address three questions critical to that pursuit: (1) what path do we seem to be on relative to goals; (2) what leverage do we have to shift direction or accelerate progress; and (3) what are the uncertainties in our understanding of our current path and our leverage?

A key purpose of this book is to report on the International Futures (IFs) global modeling system—a long-term project initiated by this author. The attention to IFs reflects the author's knowledge of that system, its special breadth of issue coverage, and its availability for use by others. Beyond IFs, the volume's more general purpose is to explore the strengths and weaknesses of the global model development enterprise as it has evolved. The models of interest here are computer simulations that integrate attention across multiple issue areas and that have a global focus (although most models minimally differentiate global regions, sometimes drill down to countries, and quite frequently even look at subnational units or geographic grid elements). They are also long-term in perspective, with horizons that often extend to mid- or end-of-century. The volume elaborates the evolution and current status of two overlapping traditions: *world modeling* and *integrated assessment modeling*.

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[1] As identified in the Sustainable Development Goals, see https://www.un.org/sustainabledevelopment/sustainable-development-goals/.

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The reader should come away with a broad understanding of existing global models, what they can and cannot do, and where global modeling might go next. The volume argues that the ability of modelers and models to address the three questions identified previously is much richer and more complete than it was a few decades ago, and that their ability to help shape desired change has increased appreciably. It also argues that much can be improved.

1.1 WHAT PATH ARE WE ON?

The Base Case scenario of the IFs system provides one image of the current path for global development across the rest of the century (see Box 1.1 for important terminology conventions used throughout this book). It suggests the possibility that in 2100 the global population will have risen to about 10 billion from 7.3 billion in 2015, with Africa's population having climbed from one-eighth to one-third of the total. We will have added about 12 years to global life expectancy, and the average woman will be having fewer than two children in her lifetime.

By 2050, the average adult will have more than 10 years of formal education and the average European more than 13 years. On a global basis, middle-class status is often defined as having daily income between \$10 and \$50 per day, and more than 45% of individuals will have attained that (with about 37% lower); even more than 50% of people in South-Central Asia (including India, Pakistan, and Bangladesh) will be middle class or higher.

BOX 1.1

TERMINOLOGY AROUND PREDICTION, FORECAST, PROJECTION, AND SCENARIO

Global modelers in all traditions avoid referring to the results of their model runs as predictions because the long-term global future is far too uncertain.

The integrated assessment modeling community typically refers to alternative model runs as "projections" (Carter et al., 2007, p. 145). The IFs project has generally eschewed that term, because it can imply extrapolation, while the many interaction effects within IFs often produce model runs with behavior quite different from the past. The IFs project term has been "forecasts," a word that much of the IAM community has considered too nearly synonymous with prediction.[2]

So, what will be the convention in this volume? Potentially we could label all model runs as "scenarios," but most modelers reserve that term for coherent, internally consistent stories about the future, not simply alternative model runs. Instead we will sometimes use the IFs convention of labeling alternative model runs as forecasts (never meaning prediction), but we will heavily and interchangeably refer to projections, especially when discussing work emanating from projects using the term.

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[2] Yet the website of the IAM named GCAM (Global Change Assessment Model) uses the terminology of "conditional forecasts," consistent with our understanding of the term. See http://jgcri.github.io/gcam-doc/overview.html.

On the sociopolitical side, the number of fully or mostly democratic countries in the world will rise from 113 in 2015 to 125 in 2050 and 145 in 2100. In 2015 an index of gender empowerment placed the average woman at about 0.45 (1.0 being gender parity); in 2100 that will still only be 0.6, in spite of women by then having five additional years of formal education and parity with men in average years of education.

On the biophysical system side, the average person (including Africans) will have access to 3300 cal per day in 2100, and 15% of people will be obese. Even so, 3% of children will still be underweight. The portion of global primary energy production that comes from oil will drop from 31% in 2015 to 14% by 2050, and the portion that comes from renewable sources will come to exceed 50% in the second half of the century. In spite of this energy transformation, the level of carbon dioxide in the atmosphere will continue to grow throughout the century, and average global temperatures will rise by 3 °C relative to those of the preindustrial world.

Almost all the preceding forecasts/projections, tied to the Base Case of IFs (*a dynamic, integrated representation of the path we seem to be on*), *will prove to be wrong*, and some quite spectacularly so, as would others with considerably shorter horizons and those by other modelers. Yet all of them are important to us because just as individuals cannot make a considered decision without thoughtfulness about consequences, societies should not decide on a significant policy action without at least implicit consideration of where we seem to be going without and with that action. Further, some projections from models will be wrong because the very making of the projections generates action against them (as with earlier ones concerning acid rain and the South Pole ozone hole).

Fundamentally important to the enterprise of building and using global models is helping others understand the basis for the current path and other scenarios that the models help elaborate. This means that their structures must be transparent. Although some argue that models need not be open for use by others who are potentially without the expertise to use them carefully, this volume argues that being open generally advances transparency, facilitates communication of strengths and weaknesses, and aides in the analysis needed to think about and improve global futures.

1.2 WHAT LEVERAGE DO WE HAVE?

There are three interacting clusters of issues of interest to those with concern about global futures. Modeling within and across these clusters is the focus of this book. Each cluster has an associated set of questions concerning our leverage to shape desired futures:

- *The development of individual human capabilities*, including the achievement of improved health, extended education, and basic material wellbeing
  - How can we advance education and its associated capabilities?
  - How much can we extend healthy human life?
- *The evolution of social systems*, including both economies that avoid great inequality of opportunity and outcomes and governance that is transparent, capable, and inclusive
  - How (and how rapidly) can we reduce or eradicate human poverty?
  - How can we build social organizations that govern us inclusively, capably, and fairly, and in a manner that furthers sustainable human development in an equitable manner?

  - How can we avoid conflict and promote stability within our local and country-based societies and across countries?
- *The interaction of human systems with the broader biological and physical environment*, including the achievement of sustainability of physical inputs and the protection of natural systems from disruptive human outputs
  - How can we advance knowledge and technology to help individuals and societies draw upon their environments to live happily and well?
  - How can we assure that our pursuit of human wellbeing does limited damage to our biophysical environment and protects the pursuit by our descendants of their own wellbeing?

It is possible to address such questions with no model at all. One can simply extrapolate past patterns when information or data on those are available, and even do so just by eyeballing patterns and trends or fitting lines with pencil and paper. In terms of action, we can often mobilize efforts (including the pursuit of the Sustainable Development Goals) using our best understanding of what is needed, and then adjust those efforts as we learn more about success and failure.

Yet well-structured models have the ability to draw upon past data and to generate numerical descriptions of possible futures, especially in the face of potential interventions with complex synergies and tradeoffs within and across these issue clusters. In fact, it is in significant part the treatment of interactions within and across the issue clusters that make global models valuable. That argues for both significant comprehensiveness of treatment of the issues and careful attention to forward and backward linkages among them. No model can represent all global dynamics, however, and a key challenge for modeling that this volume emphasizes is determining what to include and how to structure linkages.

1.3 HOW DO WE ADDRESS UNCERTAINTY?

Uncertainties are great with respect both to the path we are on and the leverage we might have. Models suffer from both errors of commission through misrepresentations of dynamic relationships (despite efforts to the contrary) and errors of omission. Use of models requires attention to both types of error.

With respect to accuracy of representation, transparency and openness are again important for the fundamental credibility of models, their improvement over time, and their use in analysis. This volume focuses much attention on the implications of alternative choices concerning structure and parameters. Much use of models is directed to analysis of sensitivity of projections related to such differences.

With respect to the issue of omission, it bears repeating that modeling projects struggle with the drawing of boundaries and the linking of issue areas within models or via interactive use of multiple models. Further, models inherently have great difficulty anticipating shocks or disruptions to systems, including major ones such as technological breakthroughs (perhaps major life extensions or rapid advance in artificial intelligence) and catastrophes (perhaps plagues that we prove incapable of stopping or tipping of equilibria in environmental systems).

Elaborating and exploring alternative scenarios is fundamental to analysis of both uncertain causal dynamics and variables (including disruptions) not included in the models. This volume devotes much attention to broad framing scenarios that help us understand very different possible futures and to potential for models to help with the often more restricted interventions of policy analysis.

1.4 THE PLAN OF THE VOLUME

Chapter 2 provides an overview of building blocks and toolkit elements used across projects. Most readers who have thought about or perhaps even been involved in the process of creating world models (including integrated assessment models) probably picture in their minds that doing so involves the development of a large, integrated set of equations. That is, without doubt, a critical element of the process. Yet such equations are only one element in a set of processes and structures to which we often give far too little explicit attention. Those processes and structures constitute a toolkit for the development and use of global models and for thinking, even without models or equations, about global change. We use the existing toolkit underlying the International Futures forecasting system as a useful but not exclusive lens for understanding such tools and their use.

Chapter 3 reviews the historical evolution of the global modeling field in the face of changes in framing of key questions (and their possible answers) and changes in modeling capabilities. The chapter overviews the progress of global modeling and introduces many of the major contemporary integrated assessment models. It begins to help us understand more about the critical challenge of making the structures large and interconnected across issue areas (and, in fact, across the three broader issue domains of this volume), yet transparent and clear. A second key challenge it identifies is not just building such models, but using them in the face of great uncertainty. In particular, it focuses on scenario analysis as an approach for dealing with uncertainty.

Chapter 4 provides an initial overview of the International Futures system, which makes a special attempt to cross over and integrate the three issue domains. The chapter also briefly surveys both the transparency and the use-enhancing interface of the IFs system and some of the forecasting applications with it. One of the challenges for a system such as IFs is the tradeoff that this volume helps elucidate between issue domain coverage and richness of that coverage. Specifically, IFs has some special strengths in human and social development, but it does not have the extensive elaboration of environmental representation that many of the contemporary IAMs of Chapter 3 contain.

Chapters 5–7 discuss the manner in which IFs and other models represent various issues or modeling areas within human development, social change (humans in interaction with each other), and sustainability (humans in interaction with their biophysical environment). Although IFs receives substantial attention in these chapters, they also provide considerable insight into conceptual and theoretical understanding of the issues, the availability of data, transitions that we can see unfolding in those data, and the approaches of other projects to modeling of the issues. Each chapter and issue section identifies key model formulations, and by providing some comparison of forecasts/projections across different projects, highlights some of our uncertainties about the future.

Chapter 8 turns to the topic of linkages back from biophysical system change to human and social development, an issue of special attention because most models have represented relatively few such linkages. The topic is also important because it touches on the issue of possible future disruptions of global development from environmental change. The chapter devotes some attention also to technological change, another key source of possible disruption. Such disruptive forces (whether they be beneficial or harmful in their effects) are a key source of uncertainty in thinking about the future, and their discussion leads back naturally to the topic of scenario analysis.

Finally, Chapter 9 builds on the volume's discussion of global models to reflect on what has been accomplished and where potential value added might direct future efforts in IFs and in the field more broadly. It begins by considering how very different the images of the future often are across the issue domains of human development, social change, and biophysical sustainability, and how those different images give rise to quite different world views concerning the future. Those differences help frame uncertainty about the future and therefore scenario analysis, which the chapter surveys. The chapter also directs attention to the importance of augmenting broad-framing scenarios of alternative futures with more policy-focused intervention analysis—a need that requires considerable comprehensiveness of issue domain coverage, sophistication and richness in component system models, but also transparency and openness for other analysts to explore our tools and their use. Finally, the chapter lists some of the potential focal points for future developments in global modeling.

At its core, global modeling is about understanding the way the world works—and about representing that understanding in a sufficiently formal yet transparent, intelligible, and communicable manner to allow credible exploration of alternative futures. Thus global modeling should be of interest to anyone who thinks seriously about enhancing human development, social change, and the sustainability of human activities. Everyone has a mental world model, and building or using a more formal one can greatly enrich the mental one and our collective efforts to improve global futures.

References

Carter, T.R., Jones, R.N., Lu, X., 2007. New assessment methods and the characterisation of future conditions. In: Intergovernmental Panel on Climate Change, Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report. Cambridge University Press, Cambridge, UK, pp. 133–171.

CHAPTER

2

Building a Global Model: The Toolkit

The process of building a global model is iterative and cumulative, with many elements of trial and error. It most definitely does not involve the careful creation of a blueprint and then the construction of a model following that blueprint. As in most science, the iteration is across conceptualization, creation, and testing or use of structures. The process includes constant evolution in the design of model systems and frequent destruction or abandonment of earlier work, more like that of a composer creating a symphony than a contractor building a house.

Further, it is not just world modeling that is relatively new; it is also our understanding of the global systems and processes that we are trying to represent. Analysts (with or without models) often emphasize the arduous, incremental, and critical process of obtaining and enhancing "domain knowledge" with respect to global change.

In the most general terms, there are six sets of activities and associated tools in the iterative model-building process:

- Identifying concepts individually and in systems
- Assembling data
- Understanding ongoing transitions in key variables
- Creating dynamic formulations, including key equations and more
- Using the model, including exploration of uncertainty
- Evaluating and addressing model strengths and weaknesses

In elaborating the toolkit, this chapter frequently refers to the International Futures (IFs) system, but the discussion applies more generally across the field of global modeling.

2.1 IDENTIFYING CONCEPTS INDIVIDUALLY AND IN SYSTEMS

2.1.1 Identifying Concepts

Concepts are the basic building blocks of all theory and understanding. Elaboration of conceptual taxonomies provides a foundation for insight into change. Darwin could not have constructed his theory of evolution (in fact, a dynamic model of long-term change) without having identified species and developed a huge database about them. Similarly, global

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modelers cannot think seriously about population dynamics without the concepts of fertility and mortality; about economies without supply, demand, and exchange; about health without mortality and morbidity (illness or disability); about education attainment without the concepts of access, persistence, and completion (or lack thereof); and on and on across other issue areas.

In each issue area, global modelers look to the experts and the cumulative literatures in the field for the key concepts. Yet dynamic representations often require an integration and coherence of thought that pushes scientists to identify variations on existing concepts, or even new ones. For Charles Darwin, understanding similarities and differences in species led to concepts of natural selection (based on survival and reproduction advantage) and to evolution itself. For those studying economic growth, critical concepts have long included capital and labor supplies, augmented by identification and elaboration of multifactor productivity. Similarly, understanding of disease required better understanding of its incidence and led to development of germ theory. More recently the concept of groundwater availability has been elaborated with the understanding of aquifer recharge and the concept of fossil water. Like other scientists, global modelers sometimes need to refine, extend, or even build new conceptualizations.

2.1.2 Recognizing Systems

As the preceding examples suggest, concepts belong in systems. Biologists before and after Darwin have built and rebuilt taxonomies of species, just as astrophysicists have built taxonomies for galaxies, stars, planets, particles, and energy forms. Those astrophysicists pay attention to the amount of matter and energy in the universe, including the matter/antimatter balance and the elusive dark matter not evident from energy emissions, because that accounting is fundamental to their understanding of dynamics and possible futures. We similarly need taxonomies and accounting systems in our global models.

Accounting systems can be static or dynamic. To understand the past and to think about the future, we quickly move to dynamic versions, particularly to *stocks* (variables with continuity across time) and *flows* (the elements that change stocks). For example, the genetic structures of species carry a stock of information that preserves their basic identity across time, while mutations provide an ongoing flow of changes to that information. In another example, the astrophysicists studying the universe for the estimated 13.8 billion years since the Big Bang posit a constant total stock of matter and energy across that entire time, even as they seek to understand the flows underlying transformations of those stocks within the past and future of the universe.

Accounting systems and stocks and flows exist in all issue areas of interest to modelers and are important structural foundations for our work in most of them. In demography, we track people by age and sex within and across time, including the number of people (the stock that carries over across years) and demographic flows (births, deaths, and migrations) that change that number (see Fig. 2.1, where the rectangle is population stock and ovals are demographic flows). Economics can now boast of sophisticated accounting systems. The field's social accounting matrices (SAMs) represent the flow of goods and services from and among producers, across borders, and to consumers; SAMs also track the flows of finance among

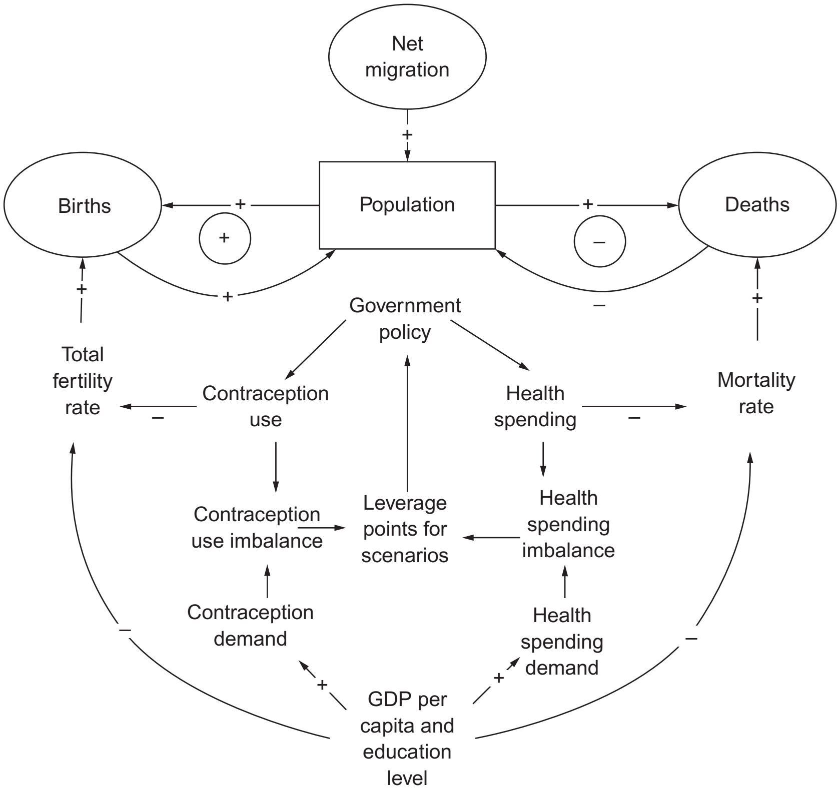

FIG. 2.1 **Stylized portrayal of demographic stocks, flows, driving variables, and feedbacks.**
Note: Not as represented in any specific model. The rectangle represents stocks, ovals portray flows, and other variables are causal; signs in circles show feedback loop valence. Source: Author.

firms, households, and governments. Production and consumption values are flows, specific to the time of creation or use. We are also interested in the stocks of the labor, capital, and know-how needed to produce those goods and services (see Fig. 2.2). Similarly, in energy we study not only annual production and consumption but also the ultimate stock of fossil fuels that supports those flows and the stock of atmospheric carbon to which annual increments from energy use contribute (see Fig. 2.3).

Thinking about and representing systems leads us into causal analysis. In Figs. 2.1–2.3, we can see augmenting and decrementing causal linkages of flows to stocks as well as other causal linkages, some of which are policy leverage points. The causal patterns often point us to positive (self-reinforcing) and negative (controlling or limiting) feedback loops. For instance, in Fig. 2.2 we see one positive feedback loop that nearly all economic models represent, namely the augmentation of capital with investment that increases with the production based on that capital. We also see a variety of negative feedback loops, including those that involve the equilibrating effects of the prices of goods and services, of wages, and of capital. Fig. 2.3 shows a second positive feedback loop—this one for energy, in which production

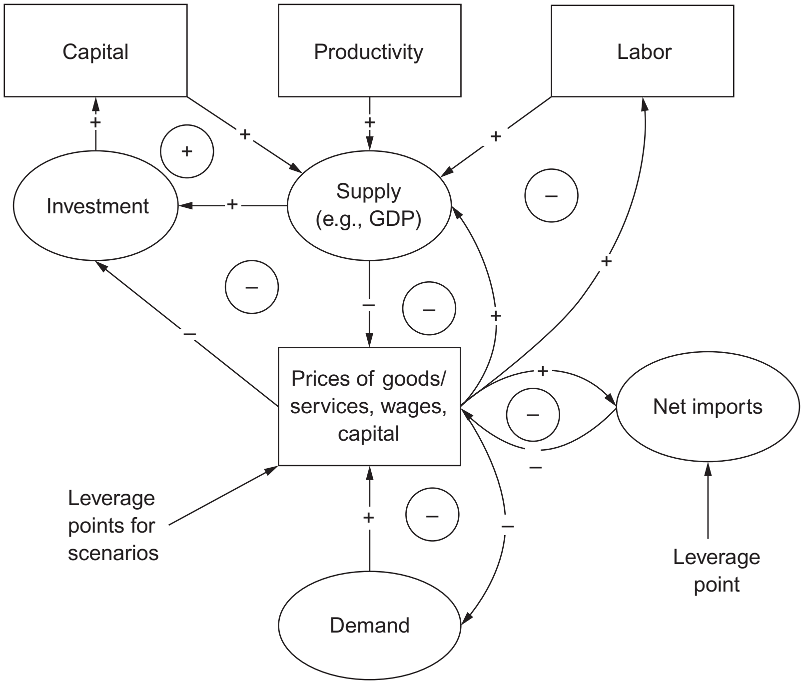

FIG. 2.2 **Stylized portrayal of economic stocks, flows, driving variables, and feedbacks.**
Note: Not as represented in any specific model. Rectangles represent stocks, ovals portray flows, other variables are causal; signs in circles show feedback loop valence. Source: Author.

enhances technological innovation (augmenting the stock of productivity) via the process of learning by doing. That could also be added to the economic model, but it is only one of many missing variables and linkages across all three stylized figures, including those that would link them with each other.

We can identify such dynamic stock and flow accounting systems pretty much everywhere, in almost all issue areas, and they are fundamentally important wherever we spot them. It may be safe to argue that they are under- rather than over-utilized in representing global change dynamics. For example, long-term analysis of fossil fuel production not tied to representation of resources (for instance, just extrapolating past patterns of production growth), or of water demand without considering supply constraints, including fossil water, has obvious weaknesses.

A basic principle that accounting systems enforce is that "there ain't no such thing as a free lunch" (TANSTAAFL). Accounting systems make sure that we do not forecast consumption without supportive production (or at least production potential), and accounting systems that combine stocks and flows ensure that we do not forecast more people without thinking about the babies necessary for a growth in population. Not all world models and integrated assessment models will use the language of stocks, flows, and accounting systems—but all will necessarily deal with these elements of understanding global change.

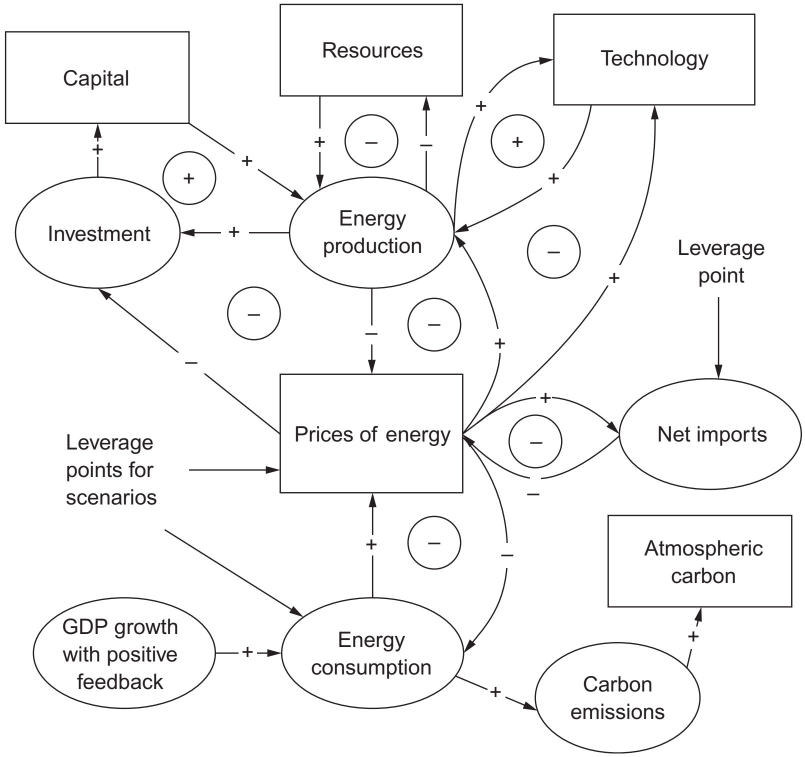

FIG. 2.3 **Stylized portrayal of energy stocks, flows, driving variables, and feedbacks**.
Note: *Not as represented in any specific model. Rectangles represent stocks, ovals portray flows, other variables are causal; signs in circles show feedback loop valence. Source: Author.*

In short-term modeling, we may not need to be as careful about either accounting systems or the relationships of stocks and flows. For instance, payments on the purchase of a new car might not immediately reduce bank assets; a surge within India in use of copper wiring and pipes may not quickly deplete warehouse stocks of the metal; annual emissions of carbon dioxide in China take years to raise the level of it in the atmosphere substantially. Longer-term analyses would be foolish, however, to ignore such connections.

2.2 ASSEMBLING DATA

Given concepts and some basic initial understanding of the accounting and stock and flow systems built around them, world modelers cast very wide nets for data, most often seeking country-year values, but also often needing data for subnational political units and, especially in integrated assessment modeling, for grids of the earth's surface. For most of us there is no such thing as too much data.

Among the greatest challenges is finding data from periods prior to the development of the concepts that began to motivate subsequent data creation and collection efforts. For instance, only in the 1930s did Simon Kuznets (1934) develop a set of national economic accounts in work for the US Department of Commerce, and only in the 1940s did that department develop gross national product as a concept of national income. It is therefore amazing and incredibly useful that Angus Maddison produced a series of books that ultimately led (with help from co-authors and followers) to the tracing of growth in national incomes around the world across a millennium (Maddison, 2001, 2003).[1] Maddison was also part of the effort that in 1974 produced the first Organisation for Economic Co-operation and Development (OECD) *Yearbook of Education Statistics* showing the flow of students through different levels of formal education and the stocks of educated people in the population by age.[2] Lee and Lee (2016) have now taken such education data back to 1820 for 111 countries, including even some former colonies. Similarly, Darmstadter et al. (1971) looked at global energy production, consumption, and trade back to 1925, while Singer and colleagues (Singer and Diehl, 1990; Small and Singer, 1982) and the Polity Project (Marshall et al., 2016)[3] help us understand conflict and governance, respectively, back to the early 1800s.

In more recent years, types and sources of data have proliferated, often within the United Nations family of organizations, including the World Bank's online World Development Indicators. The IFs project has drawn data from an extremely wide range of international organizations, academic projects, think tanks, and nongovernmental organizations, from which it has built its own database of more than 4200 series. These reach back at least to 1960 when possible, that year being the beginning of the period in which African countries gained their independence, and therefore the first year of truly global data from many international organizations.

The emergence of many data sources for the various issue areas of world modeling has given rise to new problems, including understanding the strengths, weaknesses, and idiosyncrasies of potentially similar series. For instance, the International Energy Agency, the US Department of Energy's Energy Information Agency, and British Petroleum all produce useful energy statistics. However, their estimates can differ, in part because of variability in their conceptualizations and treatments of key issues, such as whether to report the energy value of electricity in terms of the energy content of fossil fuels used to produce it or the final energy value of the electricity itself (which will be lower because of the energy lost in the conversion process).

There are also more prosaic but very real challenges in obtaining and handling data, including reconciling data in different units (including also physical versus currency values), addressing different base years for constant value currency units (e.g., $2005 or $2011), and even simply the different country names that different databases use. Not least, of course, is dealing with missing and, even worse, obviously erroneous values.

As the analyses of world models have become increasingly of interest to policy advisors in national governments, international organizations, consulting services, and other bodies, another complication has been added to the mix—namely, the desire for timeliness of the base

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[1] Maddison began with *Economic Growth in the West: Comparative Experience in Europe and North America* (1964), pushing back the historical perspective on Western European economies to 1870.

[2] See page 21 in Maddison's brief autobiography at http://www.ggdc.net/Maddison/Personal/Autobiog1994.pdf.

[3] See http://www.systemicpeace.org/polity/polity4.htm for Polity Project description, data, and reports.

year and accurate values in early years thereafter. This means that there is much motivation to re-pull and update data and to rebase the models frequently.

Modelers have typically rebased their models only with great difficulty, sometimes investing many person-years in the effort. In the personal experience of the author, a government agency paid for an update of the data underlying the GLOBUS model (Bremer, 1987). When that work was done after about a yearlong effort involving several people, the agency immediately suggested that it needed another update.

That experience led to creation in the IFs modeling system of what the project calls its "preprocessor" to codify the basic algorithms—the rules and procedures—for simplifying constant data updating and reprocessing (see Box 2.1 and Hughes and Irfan, 2013). Subject to constant improvement, this artificially quasi-intelligent system has been a great boon.

BOX 2.1

IMPORTANT AUTOMATED ALGORITHMS IN THE IFs DATA PREPROCESSOR FOR MODEL UPDATING AND REBASING

Data recognition, file updating/extending. The supporting system includes a large concordance table of country names and abbreviated symbols from a great many different data sources that allows project members to pull data from each into a common data file with consistent formatting and labeling. It includes a semi-automated capability to structure a data pull of all data series from single sources and to process those as a batch for updating purposes. Among other features, this capability allows comparison of new data with older series, and the possibility of blending new data into old series rather than fully replacing old values.

Hole filling. Multiple mechanisms fill remaining holes in data, especially for the critically important first year of the model run (base year). Given 186 countries in IFs, it would be possible to use analogous countries to estimate values. Most often in IFs, however, data holes are not filled by naming analogies, but rather by using cross-sectionally estimated functions—often against GDP per capita at purchasing power parity (PPP)—to determine a value that represents countries at similar development levels. Sometimes multivariate functions, mostly similar to those used in the forecasting itself, serve for estimation. More generally, the project has integrated basic statistical analysis tools into the software to undertake longitudinal, cross-sectional, and panel analysis, tools that then partially automate the creation of such hole-filling functions. Certain especially important variables cannot be estimated this way: GDP (both at market exchange rates and at PPP), population, and land area stand out. The IFs project designates these "essential series," requiring off-line, research-based, hole-filling procedures to assure a complete set across all countries or subunits of them.

Data prioritization, reconciliation, and cleaning. When there is more than one source of data for a variable it is necessary to assign priorities to the sources (e.g., looking to energy production data from the International Energy Agency prior to those from British Petroleum's annual *Statistical Review of World*

Continued

BOX 2.1 (*cont'd*)

Energy because, in part, of the more extensive coverage by the former). The system also compares and reconciles physical- and currency-based values. It sets maximum or minimum values to protect against out-of-range data.

Normalization. Total global exports should add up to global imports but do not, even in standard data sources. That is also true of inward and outward flows of migrants. Value added across all sectors of a country should add up to GDP, but may well not. In these instances, a residual term could be maintained (another algorithm), but IFs takes the average of total exports and imports (similarly for migrants) and imposes that on country-specific values via normalization. The algorithm for value added normalizes sectors to GDP, assumed to be the better data point. Variations of normalizing to an average, or to a value with priority, exist for other data series also.

Spreading values. For some series, and particularly with respect to age-based or cohort-specific variables, data are not compiled and made available for every year. For instance, the United Nations Population Division presents age-sex population, fertility, and survival rates in five-year categories. It is important for IFs and other models that run in annual time steps to spread five-year cohort data to one-year cohorts to avoid a computational problem called numerical diffusion (for example, an increase in five-year-olds in one year should not lead to an increase in 10-year-olds in the next year just because five to nine-year-olds are treated as one category). Similarly, values for the average years of formal education attained by adults need to be spread across years of adult age.

Calculation of basic growth rates. In runs of the IFs system, causal relationships often generate annual growth rates of variables. However, historical growth rates themselves carry important information, and IFs sometimes phases in causal relationships to replace initial trend-based growth. In such situations, establishing an initial data-linked value for the growth rate can be tricky. Because historical growth rates often vary considerably year to year, it is seldom appropriate to use data only from the two most recent years to compute the initial growth rate value. Instead, the preprocessor of IFs will often compute an average growth rate over a period of five, or even more, prior years.

2.3 UNDERSTANDING PAST AND ONGOING GLOBAL TRANSITIONS

Having important concepts and historical data series that represent them, it may be tempting to fit lines to those past patterns and extrapolate trends or patterns forward. Especially in shorter-term forecasting that is often the right thing to do, because trend momentum can be powerful—as any stock market analyst will confirm. Yet forecasters know that "a trend is a trend is a trend … until it bends." In the longer term, trends always bend.

Population forecasts made in the 1960s and 1970s demonstrate the error of using simple extrapolation for long-term modeling. During those decades it was common to see projections that extrapolated the past trend of global population growth with an exponentially rising curve (in fact, because of historically accelerating growth rates, the anticipated progression could be even super-exponential). Such forecasting made great impressions on those who saw it, but was deeply misleading because it did not take into account an underlying structural transition in fertility at work (from high to low) that would slow population growth and, we now anticipate, cause it to peak in this century.

As in this example around population, the bending of curves is very often the result of an underlying transition in some process that might superficially look like a trend that will persist. Consider global economic growth, a process that has continued for millennia. In the longest view, the human economy has progressed through hunter-gatherer, fixed agriculture, and industrial stages. Over the narrower scope of the last century, the industrial economy has been transformed by new materials and new uses of them, by its spread around the world, and by the emergence of an information- and knowledge-based economy. In fact, like agriculture, the industrial sector is now steadily shrinking in relative size. Similarly, the energy sector has undergone long-term transitions from solely human-powered to the use of wood for cooking and heating and animals for strength, to harnessing wind and water power, and to the use of fossil fuels. Since the early 1900s, fossil fuel usage has transitioned from overwhelmingly coal to mostly oil and gas, and it is increasingly supplemented by the emergence of new ways of using wind and sun. In looking ahead across the long term, it is, of course, possible to ignore such underlying structural transitions and focus on the progression of summary variables, such as the size of the economy or the amount of energy harnessed. It is seldom desirable.

In fact, there are structural transitions taking place in nearly every issue area that interests world modelers. With respect to education, women have moved rapidly toward parity with men in enrollments around most of the world, and, in fact, now have higher tertiary enrollment rates than men across most high-income countries. In health, the noncommunicable disease burden is rapidly supplementing and even replacing that of communicable diseases in country after country. In governance, although democratization has progressed unevenly (to some extent in waves), across centuries it has spread to higher and higher portions of humanity. With respect to the environment, urban air pollution has risen but then fallen in cities around the world, forest area decline has shifted heavily from temperate to tropical forests (with many temperate forests now recovering), and significant portions of increased carbon in the atmosphere are now acidifying oceans.

In summary, it is difficult to think seriously about change in global systems across this century without seeking to understand such transitions or transformations. The danger of making bad decisions by extrapolating without understanding the structure of underlying systems is great.

Looking at trends *and* transformations across the sweep of history is a powerful analytical tool. So, too, is trying to understand the patterns of developmental change across global geography. Latin America, Asia, and Africa will not precisely follow European patterns of change in literacy and education, life expectancy, economic activities, use of energy or telecommunications, governmental systems, value secularization, or much of anything else. However, those continents can be expected to follow European patterns in many respects.

Structural economists (e.g., Chenery, 1979; Chenery and Syrquin, 1975) and modernization theorists (e.g., Lerner, 1958) have drawn criticism for suggesting, or even arguing, that there are common patterns of development through which peoples around the world move. Groups of people recognize their cultural distinctiveness. Yet we observe much commonality. Literacy and education are advancing almost everywhere, and almost everyone, everywhere, desires them; similarly, people generally value longer life, greater access to advanced energy and communication forms, and inclusion in societal decision processes.

In our forecasting work within the IFs project, we look repeatedly at two major variables that correlate highly with each other (see Fig. 2.4) and with most other human and social development variables: GDP per capita at PPP, and average years of formal education attained by adults. These two developmental variables do not, of course, advance in lockstep across time and geography. Partly because of the legacy of communism, Eastern European and Central Asian countries fall above the central tendency for education levels that we see in other countries at similar levels of GDP per capita. At the same time, for a variety of developmental reasons, including plentiful oil wealth, the education levels of the populations of Middle Eastern countries fall below similarly rich countries. Nonetheless, the two variables help us frame the deep or distal patterns of development across countries and time, to which other distal variables (including technological advance and cultural change) and a plethora of more proximate variables (including policy choices) contribute.

This volume will often show developmental variables across the four country-economy categories of the World Bank: low-income, lower-middle-income, upper-middle-income and high-income. Developmental paths will not always be consistent, but the portrayal can provide insight into some of the transitions we might see, albeit with variations.

2.4 BUILDING DYNAMIC FORMULATIONS: EQUATIONS AND MUCH MORE

Having concepts, data, and an understanding of past transitions or patterns of change, we may be tempted to move with statistical techniques to estimating a concept of particular interest simply as a function of one or more other concepts. We should be cautious about doing so because our accounting systems and our recognition of causal dynamics, including those around stocks and flows, can give us a great deal of information to build more robust model structures. A foundational step is often the representation of those structures diagrammatically (see again Figs. 2.1–2.3). Those causal diagrams and the purposes of our modeling will help us make some basic decisions about the kind of model we will construct.

2.4.1 Making Fundamental Choices Concerning Model Type

There is no standard typology of global models. It can be useful to think about them along two dimensions: (1) extent of structural representation, and (2) treatment of time.

Models can range from having very limited to very complex structural elaboration. On the limited end of the spectrum, for many purposes it is a common practice to estimate a single equation (or a very small number of them) with a variety of driving variables, without

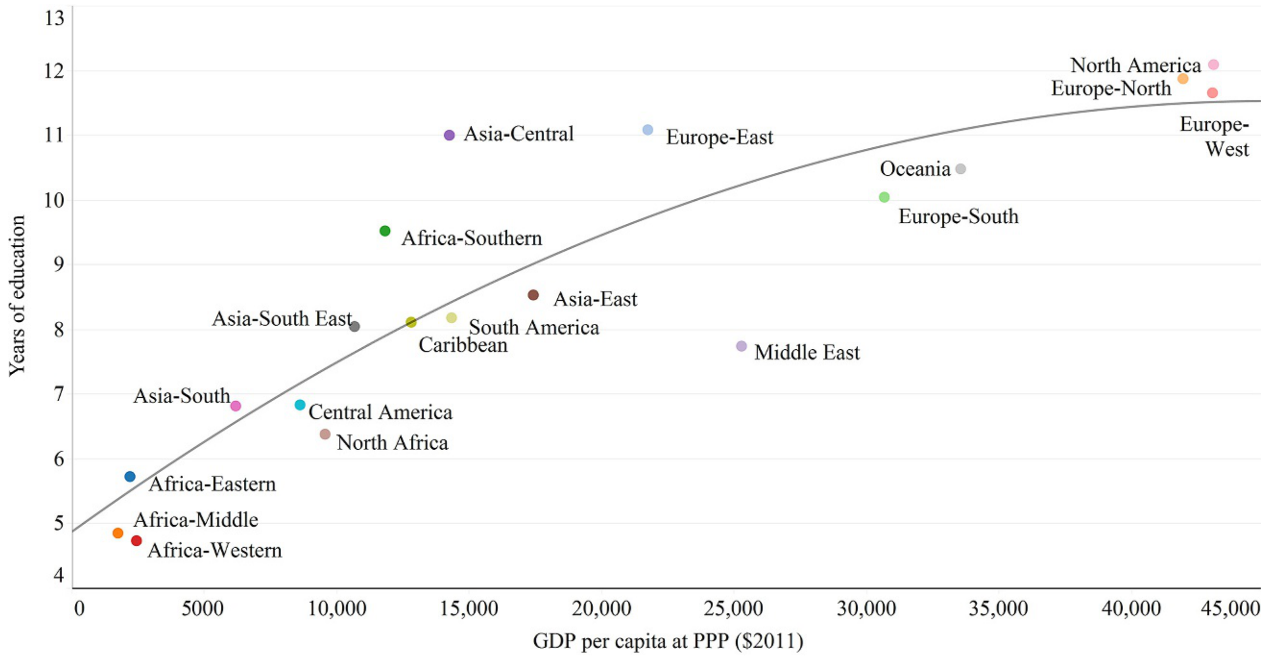

FIG. 2.4 **Global relationship between GDP per capita and years of education of adults 15 and older in 2015.**
Note: *Uses United Nations subregions (names somewhat changed) and second-order polynomial fit (r-squared = 0.85). Source: IFs Version 7.36, using years of education of adults 15 years and older from Barro and Lee at www.barrolee.com/, and GDP per capita at PPP ($2011) from the World Bank's World Development Indicators.*

distinguishing stocks and flows or considering feedback dynamics. For example, stock market analysts are interested in anticipating equity price changes, health experts want to understand the implications of lifestyle choices for heart disease, and social scientists want to understand the impact on domestic stability of government regime type and services provided. Motivation is often to understand the past (sometimes as theory testing) or immediate future, not to look ahead very far, and those who estimate equations or create models in academia and policy analysis therefore frequently make no effort to project their driving variables (or even to select drivers that lend themselves to forecasting).

Statistical models can be very rudimentary compared to the longer-term and more structurally elaborated world models of primary interest to us here. Earlier discussion in this chapter concerning representation of stocks, flows, and accounting systems already suggested that most global modeling lies much nearer the elaborate structural end of this spectrum. That is not to say, however, that extensive structural representations characterize all elements of global models. In the case of IFs, most submodels (including the critical demographic and economic models) are structurally elaborated, but others are not; for instance, the representations of governance and international politics use simpler causal frameworks.

With respect to time, we can distinguish three types of models: (1) comparative static systems, (2) systems that are recursively dynamic across time, and (3) those that use intertemporal optimization. In each case, there can be either simple statistical or elaborated structural representation.

Comparative statics modeling generally represents quite complex systems, with feedback loops and potentially with clear distinction of stocks and flows, with the purpose of understanding what might happen if the system were shocked in some manner. Such modeling is often used for the economy with its multiple feedback loops; analyses can include the impact of changing trade tariffs or interest rates.

Typically, after introduction of the intervention, the comparative statics model is run iteratively until values stabilize, showing the magnitude of changes in all variables from their values without the intervention. A variation, however, is to structure the intervention to exogenously represent change across time in one or more key variables of the model (for instance, population and/or GDP); in this case, the solutions generate new outcomes at time intervals in a *static sequential model* variant of comparative statics modeling. In static sequential models, variables computed in each time step do not endogenously carry to the next step, in distinction from recursive dynamic models (discussed next).

Recursive dynamic models represent intertemporal change, and stocks and flows can be especially important to them, in part because flows generally are temporally specific (such as births per year, annual investment, or energy consumption in a specific time interval) and stocks can carry accumulated flows across time. Recursive systems (such as IFs) often step forward across time in one-year steps, and the dynamics of change tend to be quite fully endogenous, with extensive attention to representation of causal drivers of flows (such as the fertility and mortality rates in Fig. 2.1). Demographic modeling commonly uses recursive representation, but it is possible to use it for all systems of interest in world modeling. Recursive modeling can be very useful also for linking models across issue areas because it then builds on the endogenous representation of key relationships across those issue areas. Specialized systems dynamics software is available to support such modeling, but it is not required.

Intertemporal optimization models facilitate the addressing of such questions as "what is the least cost energy mixture possible across this century to keep atmospheric carbon levels below a level that limits temperature rise to 2°C?" Stocks and flows again interact with most such questions—the feasible energy supply pattern in 2050 will certainly depend in part on energy capital stocks accumulated in previous years. Most world models using optimization do so intertemporally. That is, they look at all time points simultaneously (or iteratively back and forth) in the search for optimization strategies. Thus an optimization model looking out across the century faces a tremendous number of possible development paths to least cost energy or other goals, and computation involves iterations that can take much time even with the most powerful computers. Many or most such models use exogenous specifications of population and economic growth, thereby narrowing the paths considerably; those that include economic models to compute economic growth endogenously tend to use comparative static models solved at intervals. The solution complexity of the approach has led much work within it to rely on separate models of multiple issue areas that are "soft linked." That is, one model is solved and the results of it are then fed to others. It is easier for recursive systems to be fully hard linked. Soft links can introduce complications because iterations across separately computed models are challenging and time-consuming; as a result, feedbacks across systems may be limited.

In this volume, our interest is almost entirely in recursive and intertemporal optimization models with extensive structural representation. Given the size and complexity of both types, and for that matter given the fact that all models are simplifications of reality, further decisions are necessary.

2.4.2 Making Choices at the Systems Level

Regardless of the modeling approach and the nature of system linkages, there are major choices to be made around the representation of the larger systems within them.

2.4.2.1 *Identifying Important Feedback Loops*

Specific formulations in world models will almost always be part of complex systems with many feedback loops (like the representations of Figs. 2.1–2.3). Unconstrained positive loops generate dynamics of ongoing growth or decline that are fundamental to representing processes from economic growth to collapse of a fish stock. Almost any process that exhibits ongoing, unidirectional change illustrates a positive feedback loop at work. Again, however, given that trends ultimately bend, such processes often generate growing pressure for system disruption or transformation. Thus studying positive feedbacks can be useful for illustrating potential dangers and possibly helping society create new controlling feedbacks. Similarly, identifying and representing negative feedback loops, such as price adjustments in the face of collapsing fish stocks, can illustrate useful features for stabilizing systems to limit undesirable outcomes.

2.4.2.2 *Building Algorithms*

Algorithms are logical procedures or rule sets. In global modeling they are quite probably as important as equations or even more so, and they can range from simple normalizations to maintain accounting fidelity to the mechanisms that control optimization procedures. Box 2.2 describes examples.

BOX 2.2

IMPORTANT ALGORITHMS IN MODELING

Limiting. Functions used for very long-term analysis can produce values that exceed reasonable numbers (for instance, many variables should never have negative values or be larger than 100%). Model code frequently uses maximum or minimum functions to avoid that outcome (e.g., forcing the larger of a computed value and zero so as to avoid negative numbers). More sophisticated versions of such limiting smooth the approach of a forecast series to its specified limit over time.

Moving averages. Another type of smoothing is the use of moving averages. This is common if a driving variable is subject to considerable year-to-year volatility, while the driven variable will logically respond slowly to such change.

Normalization. It is sometimes important that the sum of a variable across multiple categories equal the value of a category total computed separately (like government expenditures). Normalization handles that by imposing the total on the sum across categories.

Shift factors. Very often, a function used to compute a forecast variable will produce a value in the first model year that is inconsistent with data. This is, in fact, basically inevitable because no function will explain all the variation in the dependent variable (consider, for instance, cultural differences around the world in the demand for meat or fish in diets, even in countries with comparable incomes and education). It would be possible to override the data values in the base year with the computed ones, but that is generally unsatisfactory, especially in policy analysis. Another approach (the one taken in IFs) is to compute a "shift factor" in that base year representing the difference between data and computation as an additive or multiplicative factor.

Convergence processes. The shift factors discussed previously could be used to adjust the computed variable in all subsequent years. Yet we know that the discrepancies between the historical data values and the computed values can reflect either errors in the data (including failures of country statistical offices to follow appropriate international guidelines) or shifts that may erode over time (such as a cultural preference for fish in the diet). Convergence functions in a model allow the shifts to disappear over a set number of years, linearly or more smoothly. Using them is generally a judgment call on the part of the modeler.

Equilibration. Markets for goods and services respond to prices, and modeling systems represent the feedback signals of prices to supply and demand to cause the model to simulate the pursuit of equilibrium. As the text indicates, the algorithms can be structured to find equilibrium in each time step (often economic models iterate until price equilibrium is attained or use analytical solution methods). IFs does not do that—instead, its inventories are stocks that rise and fall around target levels across time and generate price rises or declines, but inventories are never exactly where their holders want them to be. Chapter 6 describes the algorithm, based in control theory, that IFs uses for this equilibration process and others (e.g., around interest rates and around government revenues and expenditures).

Optimization. As discussed in the text, many global models seek to optimize some variable, often in the search for a policy recommendation, such as how fast to phase

Continued

BOX 2.2 (*cont'd*)

out fossil fuel use to limit atmospheric greenhouse gas rise below a set level. Such optimization generally requires that the model computations in any year have knowledge of what impact those computations will have in future years. That is, optimization can build in perfect foresight in contrast to the ignorance of the future (myopia) that more recursive models represent as they calculate step by step across time.

Specialized algorithms. There are many specialized algorithms in the IFs system and other models, such as for inversion of the input–output matrix and calculation of Gini coefficients (a measurement of distribution across a population) from Lorenz curves (a graphical representation of the distribution of a variable). A value of packaging such algorithms in the system, or using off-the-shelf software that includes them, is their availability for general use across the modeling system, such as the calculation of Gini indices globally for education attainment or life expectancy, in addition to their usual application to income.

Other algorithms. It is very difficult to know where to draw the line with respect to listing algorithms in world models. Processes for scaling numbers, or even for summing or averaging them, are algorithms. And after a model is run, a user interface like that in IFs is essentially a large compilation of algorithms for analyzing supporting data, presenting forecasts, and building new scenarios.

Many algorithms relate to representation of feedback systems. They might be as straightforward as specifying total arable land area as a fixed constraint on expansion of land area devoted to crops. But many are more complex, such as the adjustment of prices in market equilibration of supply and demand. In comparative static models and in intertemporal models that represent progressive static states across time, precise equilibration is generally achieved via iterative solution algorithms in each time step for supply and demand of labor, capital, and goods and services in what is called computable general equilibrium (CGE) modeling. Yet many economists (not least Keynes) and most policy analysts conceptualize the market system as one generally in disequilibrium, even while normally chasing equilibrium over time. Further, the representation of government revenues and expenditures is one of many other areas where equilibration-seeking rather than equilibration-finding algorithms make sense; while they are almost never in balance, there is the necessity of avoiding huge imbalances over long periods of time. The IFs system includes algorithms for such chasing of equilibria.

2.4.3 Making Choices at the Equation Level

Our attention to decisions about overall model character and to development of algorithms emphasizes that world models are much more than a set of individual equations. Nonetheless, the equations warrant much attention.

2.4.3.1 Seeing That Formulations Do Not All Merit the Same Attention

Some equations are more important than others. Consider again fertility and mortality within the context of long-term historical transitions in demographics. Study of historical change indicates that both flow variables (births and deaths) are important, but that death rates have fallen around the world and are now much less rapidly changing and less variable than fertility rates. Thus in the absence of an assumption that death rates might again change significantly (for example, as a result of plagues or medical breakthroughs in life expectancy), forecasting of population dynamics must pay special attention to births and birth rate, generally represented in terms of the total fertility rate (TFR), the number of children the average mother will bear in a lifetime.

In economics, we similarly recognize that both production and consumption are flows, but that in the long term consumption behaviors change in a quite common pattern with higher income (for example, after food and other basic survival needs are satisfied, people shift to manufactures and services). It is production level (a flow based on stocks of capital, labor, and knowhow) that is of especially great interest to us and to which we should give special attention.

In addition to equations having differential importance within a particular issue area and the modeling of it, equations or focused sets of them also have differential importance with respect to the interaction of issue areas. Two of these can be noted illustratively. The first is economic production, and especially the joint productivity of capital and labor—what is known as either total factor productivity (TFP) or multifactor productivity (MFP). This is a critical equation set because productivity is a function of human capital variables (like education and health of workers), social capital (including the character and quality of governance), physical capital (such as infrastructure), and knowledge capital (including R&D and technology imbedded in imported goods or capital). Chapter 6 includes a discussion of how IFs brings together these influences in the representation of production, making it a very important focal point of the larger system. A second example is around government expenditures. These can go to people as transfer payments (increasing or decreasing economic inequality) or into various areas of direct government spending, including the military, health, education, infrastructure, and R&D. In the development of societies, decisions around such expenditures are very important, and representation of them can help tie together elements of separate models, including economics, infrastructure, population, health, education, and governance. Chapter 6 also discusses how this is done in IFs.

In summary, ideally as modelers we should pay great attention to every formulation, but some computed variables will shape dynamics over our forecast horizons much more than others. In the discussion in subsequent chapters of modeling specific issue areas, I will routinely try to identify the functions that merit special attention.

2.4.3.2 Using Statistical Fit as a Guide, Not a Straitjacket

Structuring an equation should not be just a matter of best statistical fit. It is possible to fit a remarkably good equation to the decreasing fertility rates of Iran in the last three decades, simply linking it to time. However, using that equation in a model would soon generate negative fertility rates. Thus equation development should be a process that looks to a wide range of driving variables and structural realities. Several important considerations can direct the choice of variables and equation forms, including the existence of extensive theory and empirical work, as well as experience from building other forecasting systems. There is no reason to begin structuring all elements of a model from scratch, and many reasons not to do so. For instance, again with respect to economic production functions, they have been enhanced over many decades by a large number of scholars, and standard forms mostly serve us well. A second and often dramatically underappreciated consideration is common sense.

2.4.3.3 Considering Both Distal and Proximate Drivers

In modeling long-term change, it is useful to distinguish distal and proximate drivers. On one hand, distal drivers are driving variables that help account for long-term structural change. They may operate at some causal distance from the variable of interest, but they are structurally related to that variable, often via multiple paths. On the other hand, proximate variables are those that create shorter-term variation, often in part as intermediate variables between the deeper or distal drivers and the target variable, but often also as levers that policy or other short-term factors may influence somewhat independently of the deeper drivers.

For instance, it might be possible to model short-term changes in per capita electricity demand in municipalities of developing countries by looking to changes in temperature across seasons or at prices charged by urban authorities. However, in the long term, changes in income will be a key variable in determining that demand. Similarly, long-term variation in the extent of informality in an economy might be related most to changes in GDP per capita, while shorter-term variations in that extent might be affected by the willingness of a government to curb corruption and ease the burden of creating a new and formally registered business. In fact, income (or its proxy variable of GDP per capita) will be found as a distal driving variable in a great many formulations in IFs and other global models.

Another key long-term development variable used in the IFs project is education attainment of the adult population. For instance, in long-term modeling of change in government regimes from authoritarian to more democratic, levels of adult education give per capita income serious conceptual and statistical competition. Earlier discussion introduced these two distal variables in considering transitional change across geography and time (see Fig. 2.4) and noted that they were closely correlated, so it should not be a surprise that almost all formulations in IFs use only one or the other.

The IFs project frequently finds that the relationship between GDP per capita and a wide range of other elements of developmental change (e.g., from fertility rate to democratization to educational advance itself) is logarithmic. That is, social change happens especially rapidly at lower levels of income and then saturates. In a paper some years ago (Hughes, 2001), I discussed this logarithmic tendency in terms of the progression of social change through the stages and processes of the "sweet spot" (at low levels of national income) and the "steady slog" (in the middle-income transition and at higher-income levels). I also identified a third developmental phenomenon and labeled it the "systemic shift." This refers to the tendency for cross-sectional relationships of variables such as total fertility rate or democracy with GDP per capita to shift (downward and upward, respectively) over time. That pattern is almost certainly partially related to ideational shifts that shape attitudes, policies, and institutions globally (and sometimes to technological change, such as the advance of fertility control methods).

In summary, distal drivers, limited in number, represent the basic development trajectory. In distinction, a broader set of proximate variables represent the many influences pushing and pulling around that basic trajectory. In addition, proximate variables are often much closer to possible policy interventions than are distal ones; even so, because of fairly high levels of aggregation in world models, they more often represent policy leverage points (like increasing renewable energy production) than actual policy levers (such as subsidies to producers of wind or solar energy). Nonetheless, the addition of proximate variables to models that might otherwise be driven almost exclusively by distal variables helps make those systems more useful in policy analysis.

The process of including proximate variables is often not a simple matter of adding them into a regression equation with the distal drivers. There are serious problems with that approach, because many of the multiple policy variables that we believe would affect a dependent variable are significantly correlated with the deep distal driver to which we want to give primary control over long-term behavior.

To understand the problem, consider trying to forecast fertility rates with either GDP per capita or years of female education as a distal driver and rate of modern contraception use as a more immediately changeable policy intervention. Using data from the IFs database, the R-squared in the correlation of GDP per capita with contraception use is 0.43 (logarithmic) and that of adult female education attainment is 0.50 (linear). That of contraception use with fertility is a remarkable 0.64. Thus we theoretically could build a strong forecasting equation driving fertility with contraception and drop out both GDP per capita and education attainment. Yet in recent years, not a single country where women had fewer than three years of education had contraception use higher than 30%, and not a single country where they had more than 12 years of education had usage less than 60%. Giving the world a model in which analysts could ask what would happen if Mozambique, one of the former countries, moved in the next 5 years from 10% to 90% usage would potentially lead to a ridiculous policy prescription. Contraceptives might be handed out freely (women could even be paid to take them), but actual high rates of usage in the society would be highly improbable until women's education (and role in family decision making) advanced appreciably.

Our forecasting formulation should therefore recognize, regardless of what statistical analysis might tell us, that the distal driver will do a very large amount of the real work in changing fertility (and contraception use). There will, however, be societies—like China, El Salvador, Finland, and Vietnam—where contraception use is higher than would be expected based on the education level of women or GDP per capita, and others—like Trinidad and Tobago, Uganda, and the United Arab Emirates—where it is lower. The variation of proximate drivers (such as the strength of maternal support systems) *from expected levels* should *help* drive differences in fertility. Later chapters will elaborate such a combined distal and proximate variable approach in nearly every issue area that the volume addresses.

2.4.3.4 Looking for and Understanding Leverage Points

The stylized system representations in Figs. 2.1–2.3 also provide insights with respect to potential leverage points for policy choices. Many such leverage points affect variables that operate within complex feedback systems. Interventions at points that sit within positive feedback loops, such as capital stock in Fig. 2.2, may have very strong impacts because they accelerate those reinforcing loops. In contrast, interventions at points that sit within negative feedback loops, like energy consumption in Fig. 2.3, may demonstrate disappointing impacts. For example, reductions in energy consumption (e.g., via auto emission standards) lower energy prices, which feeds back to encourage more energy consumption (e.g., through the purchase of larger cars), a well-known phenomenon called the rebound effect. In fact, Figs. 2.1–2.3 suggest the significant number of negative feedback loops in market-centric systems, explaining why models (and the real world) tend to "fight" our attempts to change basic forecast patterns.

In discussion of distal and proximate variables, we already touched on another leverage point insight. Fig. 2.1 included two proximate variables, namely contraception use and government spending on health. Demand for both contraception and public health spending tend to grow with GDP per capita and education levels (distal developmental variables). If government policy and other forces in a society have already led to higher actual contraception or health spending values than expected at a particular development level, it is unlikely that real world intended upward interventions will have as much leverage as in a country where values are lower than normal at the current development level. In the real world, attempted push on what we might call "saturated leverage points" will likely run into other constraints that fight back against our efforts.

The IFs project often uses cross-sectional analysis of potential leverage points with development variables to benchmark whether a country is ripe for intervention in a given area. Going back to Fig. 2.4, education in the Middle East was far below what we would expect in countries at their level of GDP per capita. In this case, even the distal drivers are imbalanced. Because in some circumstances education can also be considered a proximate driver (especially when enrollment rates are well below typical levels at a country's level of GDP per capita), it suggests an important leverage point for action by governments and other actors—or possibly a grievance point for young people who feel deprived of a good education and employment prospects.

2.5 USING THE MODEL AND EXPLORING UNCERTAINTY

It is common to refer to any run of a model as a "scenario," but strictly speaking most runs explore a single, narrowly defined intervention and should be called "cases" or just "runs." Scenarios should be coherent alternative stories of the future, consistent with what Herman Kahn meant by them when he first used the term (Chermack et al., 2001, p. 10).

Most models include a default set of initial conditions and parameters that generate a run that the developers do not view as their prediction of the future (any more than is any other scenario) because there are far too many uncertainties in structures, algorithms, initial conditions, equations, and parameters. Nonetheless, building on historical patterns and dynamics, the run constitutes a reasonable analytical starting point for alternative analyses of the future. This run has many names, including reference run, current path, middle of the road, or (as in IFs) the Base Case scenario. Some refer to a "business as usual" scenario, but there are enough complex dynamics, nonlinearities, and even pattern changes in the results from global models that most projects avoid that language—it is more commonly used in scenario analysis not based on models. The future will differ from model results not just because of errors in model structures and formulations but also because of all the surprises that variables and causal dynamics not even included in the model will produce over coming years. Thus some projects refuse to identify such a core scenario and turn directly to a set of alternative futures.

2.5.1 Building Alternative Scenarios

All projects need mechanisms to allow the developers and users of the model to intervene with alternative assumptions, very often after exploration first of the reference or base case. For instance, the IFs system has a user interface that allows (1) altering of all initial conditions and equation parameters and (2) setting of values for multipliers and additive factors that directly affect the endogenously computed values of key variables.

Use of a model should involve sensitivity analysis as well as scenario analysis, although the distinction between the two is not always clear-cut. The former is often focused on understanding the response of the system to (1) changes in specific model parameters or formulations (hence more technical analysis of the model's structure and behavior) or (2) changes of variables over which we might expect human decision-making and action to have some control. The latter type of sensitivity analysis has a special role in policy analysis.

2.5.2 Exploring Transformative Uncertainty

Uncertainty is huge in looking at long-term change in global systems. As Bill Gates said, "We always overestimate the change that will occur in the next two years and underestimate the change that will occur in the next ten."[4]

Bookstaber (2017) identified four major sources of uncertainty that complicate anticipating economic futures, and they also pertain more generally: (1) emergent phenomenon (his focus was on group dynamics varying from individual preferences, but it could also encompass technological change); (2) non-ergodicity (we cannot assume human processes to follow the same rules as in earlier, similar situations, not least because of memories and learning); (3) radical uncertainty (the range of possible future outcomes is not understandable); and (4) computational irreducibility (our models can never capture all the complexity of the real world).

Because they are inevitably simplifications of reality, we repeat still again that models generally produce inaccurate forecasts. As we have stressed, world models are best understood to be tools for thinking about the future and for helping to understand global change, and thus should be viewed as one supporting element in the search for interventions to create more desirable futures. By no means should they ever be used as definitive guides to action. Enhancement of them is a continuous process and scenario analysis is a major tool.

Unfortunately, even scenario analysis has difficulty addressing one of the weaknesses of world models (including integrated assessment models)—namely, the propensity for their structures to be well behaved even in the face of many and major interventions. Modelers

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[4] See http://www.brainyquote.com/quotes/quotes/b/billgates404193.html; from *The Road Ahead* by Bill Gates, published in 1995 by Viking Press.

do not like their systems to "blow up," and testing and refinement of them often assures that they do not. That tends to generate resilience and stability in the face of even rather dramatic changes of parameter values and multiplier settings. Transformations from one relatively steady state of patterned behavior to another quite different one are very difficult to represent in models. Agent-based models can do that, but they link behavior to micro-level agents; it appears highly unlikely that long-term multi-issue global models will be built on an agent basis for a long time, if ever.

Arguably such resilience is reflective of the real world across our analytical horizons. Life may have undergone five mass extinctions over a period of 540 million years in the face of events as dramatic as systemic biological change (e.g., photosynthesis and large-scale oxygenation), large meteor impacts, and volcanic eruptions. Otherwise, change has been slower, albeit often highly significant, over eons. Nonetheless, our interest in transitions that might become transformations, and therefore in the possibility of disruptive change from tipping points, means that we would like also to build the possibility of exploring such disruptive change into modeling and scenario analysis.

Future dramatic change obviously could come from human behavior and interaction. A nuclear war and associated nuclear winter is one such change that was much discussed during the Cold War and remains possible. Dramatic change could come from environmental events such as a major plague, strike by a large asteroid, or extraterrestrial contact. Human activity is, in fact, generating two major transformations: massive species loss and large-scale climate change. Transformations might also come from technological change, including major human life extension, control over evolution, or uncontrolled artificial intelligence and robotics. World modeling increasingly needs to build in appropriate impacts of, and responsiveness to, disruptive change and the passing of tipping points, even while representing smoother change in most analyses undertaken.

Scenario analysis of change within anticipated ranges, and potentially of change outside of them, links the "how" of world modeling back to the "why." Work in all three major domains of issue interest noted earlier—human development, social development, and sustainable development—benefits from the creation of modeling systems that facilitate the introduction of scenarios and the exploration of possible behavior within them.

2.6 ASSESSING AND ADDRESSING MODEL STRENGTHS AND WEAKNESSES

Models are, by definition, simplified representations of reality and, as such, are always imperfect and subject to improvement. As Box and Draper noted (Box and Draper, 1987, p. 422), all models are wrong, but some are useful. How can we guide their improvement and make them more useful?

2.6.1 Verification, Validation, and Accreditation

The framework of verification, validation, and accreditation (VVA) articulated by Sargent (2000, 2013) can help us begin the process of model evaluation and improvement. *Verification* refers in large part to making sure the model does what we think it should. It includes preventing blow-ups and removing coding that generates obviously stupid behavior. Those problems can occur with formulations that have high statistical significance and algorithms that seem logical but result in perverse individual or system-based behavior—or that were coded badly. Modeling is a constant process of debugging and adjusting, especially in the face of stress testing/sensitivity analysis and scenario development. One risk noted earlier is that models may become too robust and stable in the face of extreme interventions.

Constant use and analysis of the system by others beyond the modelers can help identify such problems and facilitate addressing them. One of the weaknesses of world modeling in general, however, is that many systems are unavailable for use by others, and some that are open can be complicated to set up and run repeatedly (friendly interfaces are uncommon). It is challenging to verify much of our modeling.

Validation, the assurance that the forecasts/projections are "right," is not possible, even when we understand the model output to be conditional upon a set of underlying assumptions. Yet, we can take steps toward "rightness." These include the examination of results for reasonableness and logic, an extension of verification. That often involves face validity, or the comparison of behavior in scenarios with what we would expect. This step requires us to recognize our computer system as an extension of, and related to, our mental model. In fact, the development and improvement of computer models and the mental models of those creating them are iteratively interactive processes.

An important extension of this analysis of model behavior is the comparison of results both with historical periods and with other scenarios of the future. With respect to the former, many projects initialize their models in historical years, a process that builds in an opportunity to compare historical performance with data.[5] Another very simple test is displaying Base Case projections as an extension of historical data to see if the model generates unexplainable transients.

Because so many historical data series are now available back to about 1960, IFs has two temporal run modes. The first begins in 1960 and has built-in capacity for comparing run results with historical data. Among the things we have learned using this mode is that our demographic and economic forecasts for China were wrong because we were not able to anticipate either the one-child policy or the liberalization of the economy that led to a surge of growth after the 1970s. We also could not anticipate the energy shocks of the 1970s, which had roots partially in the tightening of markets following the peaking of US oil production, but also roots in the increasing control of their own oil resources by the countries of the Middle East and the oil embargo they imposed at the time of the 1973 Middle Eastern war.[6] Some of the biggest failures, requiring that we add exogenous interventions to correct them, were heavily on the sociopolitical side, an important insight for looking forward. The second temporal mode of IFs uses the most recent data we can find (usually with a lag of

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[5] For example, MESSAGE runs begin in 1990 (https://wiki.ucl.ac.uk/display/ADVIAM/Reference+Card+-+MESSAGE); the IMAGE suite shows TIMER forecasts from 1971 (Stehfest et al., 2014); and both World3 and TARGETS ran from 1900. Chapter 3 introduces these models.

[6] See Wack, 1985. His description of scenario analysis around the playing out of these forces built an outstanding reputation for his work and that of the Shell Scenarios Team.

about 2 years) to initialize the model in order to avoid some of the shorter-term errors of earlier work, when the initial model year was 5–10 years in the past. This is especially important for policy-oriented model users or clients who obviously dislike seeing analysis values that are already wrong.

Modelers sometimes refer to the historical testing of models as validation of them, as if matching history were adequate for that purpose. There really never is validation, regardless of method, only accretion of support for it. A clear danger linked to historical testing is the obvious one that "this time will be different." We recognize that a model validated to the world of the 1700s would not have performed well in the 1800s with the movement from largely monarchial, agrarian, slow-growing societies with wood-based energy systems to a world of increasingly democratic polities and industrial and faster-growing economies with coal-based energy systems. Given that we routinely discuss the acceleration of change in all spheres, that analogy should give us pause as we consider possible developments across the 21st century.

The comparison of one's own model with those of others for the purpose of validation is ideally a comparison not just of model behavior, but also of the model structures that generate it—and therefore also with the mental models of others. Chapter 3 notes the existence of recent model intercomparison projects that contribute to the global modeling validation effort. The IFs system builds many quantitative projections from other models into its file system and packaged display set to facilitate the comparison of model results. Further, the transparency of the IFs system and its openness to use by others can facilitate structural comparison. Chapters 5–8 undertake such comparison of IFs and other models.

Accreditation builds on analysis of one's own work by others and refers to the acceptance by them of the general quality of a model system and its projections. In the scientific world a large part of that depends on the reviews that accompany (and even allow) publication; on feedback at conferences, meetings, and presentations; and on the reactions of peers to material in print.

One of the dangers of both the validation and accreditation processes is herd instinct. The sharing of mental models in building our own systems and assessing those of others carries many benefits, including learning from others and identification of obvious errors, but also enhances the risk of convergence toward a mutually reinforced but incorrect understanding of the future. Whether modelers use the word or not, they routinely "tune" their own formulations and parameters so that similar base or reference scenarios frequently emerge. Using an example from the social sciences, the mental models of a very large portion of political economists in the 1970s and 1980s saw a hierarchical world in which the wealthy countries kept the rest of humanity poor by structuring the world economy in such a manner that catch-up or convergence was impossible. By the late 1990s and early twenty-first century, most economic thinking and modeling came to build in global convergence processes driven by the ability to adopt technology from richer countries and export to them. With the still more recent emergence of thinking about a middle-income trap and the loss, in part driven by technology change, of the earlier industry-based export-led path to growth, the consensus view could quickly swing yet again.

In summary, the traditional VVA approach to evaluating models is helpful, but still cannot assure quality given the range of uncertainties. World modeling is not the same as building a model to forecast temperature of a specific location over the next 3 days. As difficult as that might be, it pales in comparison with understanding the interaction of many global systems over the rest of the century.

The problems identified here notwithstanding, much of the rest of this volume, by drilling down into models, attempts to address the questions of how well we are doing in world modeling, where the state of the art and science is strong or weak, and where it might go next. In particular, the final chapter focuses on these questions.

2.6.2 Addressing Errors of Omission and Commission

In the most general terms, models are subject both to errors of omission (things that are left out) and errors of commission (things that are included that should not be or are represented incorrectly). We constantly seek to identify and address both types of errors via modeling and scenario analysis. The easiest to fix are those we know about and know how to fix. There are, of course, others that we also know about, but how to fix them is at this point unknown to us; those we work hard to research and understand. Unfortunately, there will always also be some errors of both omission and commission that are what former US Secretary of Defense Donald Rumsfeld made famous by his labeling as "unknown unknowns."

As the discussion of models proceeds in the following chapters, I will repeatedly point to errors of omission that we know about, whether or not we fully understand how to address them. These will be of specific variables, of entire systems of variables, of drivers of an included variable, and of forward linkages from the included variables. For instance, given the long-term focus of world modeling, deep developmental drivers (at least GDP per capita) are almost always present in formulations, but it is difficult to represent large numbers of the potential policy levers. Another significant category of omission tends to be endogenous or even exogenous representation of variables around major system disruption.[7] This is true not just for very low probability wild cards, such as a meteor strike, but also for highly disruptive variables with much greater probability, such as the use of CRISPR-Cas9 gene-editing technology to change the inherited genetic structure of organisms from mosquitoes to humans.

Errors of commission range across the same categories as those of omission. Among the known issues is the fact that any formulation for variable forecasting will be less than ideal—and we may or may not know how to improve it. Data for the variables in our driver set never explain 100% of the variation in the forecast variable, in addition to which the drivers of the future may be different. This is in significant part often an error of omission (other drivers, some for which we cannot have data, explain some of the residual variation), but it is also frequently an error of commission because we may have failed to use the correct forecasting forms (e.g., perhaps relying on a logarithmic relationship when some exponential form would better serve). Often we include variables that we know are not the actual or conceptually preferable causal drivers, but are the best proxies we can find for ones we really

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[7] In an October 4, 2016 article in the *Financial Times* ("There Is No Hope of a Quiet Life in the Age of Disruption"), Hal Varian argued that whereas 20th-century innovations and developments tended to be within sectors (think of cars, aircraft, radio, and television) and took time to spread globally, today's digital innovations (think of Google, Amazon, Microsoft, and Apple) tend to immediately ripple throughout the economy and across the world, as evidenced by the speed of growth and scope of such companies and competition among them. Economic forecasting models represent such disruptive change rather crudely, if at all.

would like to have. Perhaps the best example of this is the use of GDP per capita as a proxy for development level, when we know that to represent a syndrome of developmental changes we should include some as apparently remote from economic production as cultural changes. In this case, even the substitution of "better" proxies, such as GDP per capita at PPP or a broader development measure such as the United Nations Development Program's Human Development Index, would not fundamentally correct an error of commission.

Given all the possible, in fact inevitable, errors of omission and commission, how can we proceed? Or is Dante's warning at the gate to Hell ("Abandon all hope, ye who enter here") one that should deter us from proceeding at all? Two important points to keep in mind in order to avoid undue discouragement (if not despair) are that (1) all decisions require consideration of consequences using mental or other models and (2) all models, not just ours, suffer from the same types of error. We can and should bring the full force of our mental models (and other, quantified ones) to bear in conjunction with our own computer-based ones to improve our thinking about the future.

Finally, we should never treat any model, including mental ones, as magic black boxes or oracles that tell us the future. Two activities help assure that we will not. First, models should be kept as transparent as possible, allowing others to compare and contrast theirs with ours in the tradition of scientific inquiry. Some projects, including IFs, draw upon a number of techniques to build transparency into and around a model system, including extensive documentation inside and outside the model and openness of the underlying source code. Second, when others, whether they be modelers or policy advisors, use and review the behavior of a forecasting system, their feedback and review can be extremely helpful for further development and improvement of the system. Among the best decisions made in the IFs project were (1) making the system completely and freely available to others for use and (2) facilitating such use with a user-friendly interface for data analysis and scenario exploration and creation. The feedback received has been a constant stimulus for system correction, refinement, and enhancement.

The rest of this volume focuses on comparing and contrasting global models, especially their structures, but also the scenarios that they generate. It gives special attention to IFs, but ranges widely too across other models. The next chapter introduces specific global models and provides the general story of their evolution.

References

Bookstaber, R., 2017. The End of Theory: Financial Crises, the Failure of Economics, and the Sweep of Human Interaction. Princeton University Press, Princeton, NJ.

Box, G.E.P., Draper, N.R., 1987. Empirical Model-Building and Response Surfaces. John Wiley & Sons, New York, NY.

Bremer, S.A. (Ed.), 1987. The GLOBUS Model: Computer Simulation of Worldwide Political and Economic Developments. Westview Press, Boulder, CO.

Chenery, H.B., 1979. Structural Change and Development Policy. Johns Hopkins University Press, Baltimore, MD.

Chenery, H.B., Syrquin, M., 1975. Patterns of Development, 1950–1970. Oxford University Press, London, UK.

Chermack, T.J., Lynham, S.A., Ruona, W.E.A., 2001. A review of scenario planning literature. Futur. Res. Q. 7 (2), 7–32.

Darmstadter, J., Teitelbaum, P.D., Polach, J.G., 1971. Energy in the World Economy: A Statistical Review of Trends in Output, Trade, and Consumption since 1925. Johns Hopkins Press, Baltimore, MD.

Hughes, B.B., 2001. Global social transformation: the sweet spot, the steady slog, and the systemic shift. Econ. Dev. Cult. Chang. 49 (2), 423–458. https://dx.doi.org/10.1086/452510.

Hughes, B.B., Irfan, M.T., 2013. The Data Preprocessor of International Futures (IFs). Working Paper 2013.07.12. Frederick S. Pardee Center for International Futures. University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/2013.07.12_IFsDocumentation_Data_PreProcessor_v37.pdf.

Kuznets, S., 1934. National Income, 1929–1932. National Bureau of Economic Research, Washington, DC. http://www.nber.org/chapters/c2258.

Lee, J.-W., Lee, H., 2016. Human capital in the long run. Develop. Econ. 122, 147–169. https://dx.doi.org/10.1016/j.jdeveco.2016.05.006.

Lerner, D., 1958. The Passing of Traditional Society: Modernizing the Middle East. Free Press, New York, NY.

Maddison, A., 1964. Economic Growth in the West: Comparative Experience in Europe and North America. Twentieth Century Fund, New York, NY (Reprinted in 2006 by Routledge.).

Maddison, A., 2001. The World Economy: A Millennial Perspective. Organisation for Economic Co-operation and Development, Paris, France.

Maddison, A., 2003. The World Economy: Historical Statistics. Organisation for Economic Co-operation and Development, Paris, France.

Marshall, M.G., Gurr, T.R., Jaggers, K., 2016. Polity IV Project: Political Regime Characteristics and Transitions, 1800–2015. Dataset Users' Manual. Center for Systemic Peace, Vienna, VA. http://www.systemicpeace.org/inscr/p4manualv2015.pdf.

Sargent, R.G., 2000. Verification, validation, and accreditation of simulation models. In: Fishwick, P.A., Kang, K., Jones, J.A., Barton, R.R. (Eds.), Proceedings of the 2000 Winter Simulation Conference. Society for Computer Simulation International, San Diego, CA, pp. 50–59.

Sargent, R.G., 2013. Verification and validation of simulation models. J. Simul. 7 (1), 12–24. https://dx.doi.org/10.1057/jos.2012.20.

Singer, J.D., Diehl, P.F. (Eds.), 1990. Measuring the Correlates of War. University of Michigan Press, Ann Arbor, MI.

Small, M., Singer, J.D., 1982. Resort to Arms: International and Civil Wars, 1816–1980. Sage, Beverly Hills, CA.

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., 2014. Integrated Assessment of Global Environmental Change With IMAGE 3.0: Model Description and Policy Applications. PBL Report No. 735. PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands. http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2014-integrated%20assessment%20of%20global%20environmental%20change%20with%20image30_735.pdf.

Wack, P., 1985. Scenarios: uncharted waters ahead. Harv. Bus. Rev. 63 (5), 72–89. https://dx.doi.org/10.1225/85516.

CHAPTER
3

The Evolution of Global Modeling

A review of the historical progression of global modeling will help put in context the extended discussion of the International Futures (IFs) system and other models in later chapters. That history is quite short, with very little to point to before 1970.

Since its inception, global modeling has evolved rapidly in response to four developments: (1) computer capability (from mainframes with punch cards to supercomputers with remote terminals to personal computers that have the power of early supercomputers); (2) data availability (in the early 1960s, for instance, there were practically no data on the new African states); (3) software support systems (statistical packages, object-oriented computer languages, specialized modeling languages, and user interface support have emerged or changed dramatically); and (4) increasingly sophisticated predecessor systems that newer models can build upon.

This chapter proceeds in three steps:

- Description of the early history and foundational work of world modeling
- Discussion of the more recent development and use of integrated assessment models
- Reflection on the current status of global modeling and some of the challenges we now face in building and using modeling systems

3.1 EARLY GLOBAL MODELING WITH MULTIPLE-ISSUE, LONG-TERM SYSTEMS

3.1.1 Foundational Work

Under the leadership of Nobel Prize-winner Lawrence Klein, Project LINK began in 1968 to build a global economic model by connecting domestic economic models from many countries via trade (Ball, 1973; Klein and Su, 1979). The project continues today as the World Economy Forecasting Model (WEFM), with leadership at the University of Toronto and the Development Policy and Analysis Division of the United Nations Department of Economic and Social Affairs. The time horizon of forecasting with it is short, however, and the system still focuses on economics rather than on multiple issue areas.

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It was the work at MIT by Jay Forrester, described in *World Dynamics* (Forrester, 1971), that initiated an entirely new genre of computer-based models, moving beyond a single academic discipline or issue area and extending the time horizon from a few years to multiple decades. A group of Forrester's then students—Donella (Dana) Meadows, Dennis Meadows, Jørgen Randers, and William Behrens—built the World3 model with Forrester's work as the foundation and used it to write the famous and controversy-generating report to the Club of Rome called *The Limits to Growth*, as well as its technical documentation (Meadows et al., 1972; 1974; see also the Meadows et al. (1992) update, and the related spreadsheet model-based forecasting of Randers, 2012). World3 represented the world as a single geographical unit, forecast from 1900 through 2100, and treated five major substantive areas: the economy (three sectors), population (four age categories), agriculture, resources, and the environment. The MIT models used a modeling technology developed by Forrester initially in the 1950s—namely, systems dynamics with its very conscious attention to stocks, flows, drivers of the flows, and feedback loops (see Forrester, 1968).

3.1.2 The First Wave

Even before the publication of *The Limits to Growth*, the team of Mesarovic and Pestel in the United States and Germany began to develop a World Integrated Model (WIM) that supported the second report to the Club of Rome, *Mankind at the Turning Point* (Mesarovic and Pestel, 1974a). That model elaborated geographical coverage to 12 regions of the world and population into 86 age categories, and it similarly built out multi-category representations of the economy, energy, food, materials, and more.

Other *world models* followed, including one at the Bariloche Foundation in Argentina with a more normative orientation and a heavy focus on less-developed countries; it supported the publication of *Catastrophe or New Society? A Latin American World Model* (Herrera et al., 1976). From Japan came the Future of Global Interdependence (FUGI) model (Onishi, 2002), while the Systems Analysis Research Unit Model (SARUM), stratifying the world by income level rather than geography, emerged from the UK Department of the Environment (Roberts, 1977).

Between 1974 and 1981, the International Institute for Applied Systems Analysis (IIASA; founded 1972) hosted nine Global Modeling Symposia highlighting many of the early world models (Siegmann, 1987); for an example, see the report of proceedings by Mesarovic and Pestel (1974b). Subsequent publications by Brecke (1990), Cole (1977), Hughes (1980, 1985), Meadows et al. (1982), Onishi (2001), Richardson (1982), and Siegmann (1987) compared and contrasted many of the early models. The issues that motivated the building of these models were primarily environmental resource constraints like those that appeared with the oil and food price shocks (and African famine) of the 1970s and, secondarily, human development.

Models also continued to appear with a mostly or entirely economic focus, including one based on Leontief's input-output structure (Leontief et al., 1977) and the World Bank's SIMLINK (Hicks, 1975) and Hickman (1983) provided a review of many of them. Other more specialized models treated areas such as global energy (Cazalet and Stanford Research Institute, 1977) and agriculture, as in Linnemann's Model of International Relations in Agriculture (MOIRA) (IIASA, 1977).

3.1.3 New Capabilities

The world of global modeling changed in the 1980s and 1990s, in significant part because the collapses of energy, food, and other commodity prices shifted attention away from the focus on environmental resource constraint that was so great in the models of the 1970s. The new models during this period reflected the rise of attention to other issues. For instance, in the early 1980s the GLOBUS model at the WZB Berlin Social Science Center (Bremer, 1987) moved heavily into international politics (a wall still divided the city and the Cold War was in full swing) and political economy (global exports plus imports as a ratio to GDP surged from 26% in 1965 to 39% by 1990, signaling the unfolding of an era of globalization not unlike that near the beginning of the 20th century).

An even greater influence, however, was rapid growth in understanding of the buildup of atmospheric carbon and its possible impact on climate. Attention to the impact of ozone-depleting chemicals had risen somewhat earlier, helping to support the push for the Montreal Protocol agreement of 1987 to control them; that experience had relatively limited impact on world modeling but helped shift attention to the atmosphere. Two United Nations agencies established the Intergovernmental Panel on Climate Change (IPCC) in 1988. Integrated assessment modeling, with attention also to issues like acid rain as well as greenhouse emissions, became a recognizable scientific effort in the late 1980s.

During the same period, advances occurred in modeling within specific issue areas, including economics, driven in part both by the need for analysis of ongoing trade liberalization and climate change. The Michigan Model of World Production and Trade (Deardorff and Stern, 1986) supported analysis of the Tokyo Round of Multilateral Trade Negotiations; the World Bank's LINKAGE model (van der Mensbrugghe, 2011), with roots in the 1980s, similarly supported trade negotiations including the Uruguay Round. On the climate side, the GREEN model (Lee et al., 1994) of the Organisation for Economic Co-operation and Development facilitated analysis of the costs of carbon dioxide abatement.

With respect to the evolution of world modeling as a field, we also should not underestimate the impact of changing hardware and software technology and of data availability. Although the first personal computers were too limited for any significant models to be built on them, already in the early 1980s a very scaled-down version of the International Futures (IFs) system emerged for early Apple and IBM system usage. By the 1990s it had become possible to build medium-scale models on desktop and then laptop systems.

Building on those new capabilities, the Stockholm Environment Institute-Boston developed the PoleStar System (Raskin et al., 1999) in large part to support the efforts of the Global Scenario Group[1] (Electris et al., 2015; Raskin et al., 1998, 2010); in early phases PoleStar was also available for download and use on personal computers. PoleStar focused both on developmental systems, such as demographics and economics, and environmental/resource systems, including agriculture, energy, water, and pollution. It represented a computational framework more than a traditional dynamic model, drawing together accounting systems without extended temporal dynamics. Nonetheless, it allowed its users to input and understand environmental impacts of changes in developmental drivers in a

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[1] Established in 1995 by the Tellus Institute and the Stockholm Environment Institute.

coherent and integrated fashion and to elaborate alternative quantitatively supported scenarios.[2] Although the PoleStar system is no longer being actively developed, the scenarios of the Global Scenario Group have had wide impact. Variations of them framed the forecasts of the third and fourth Global Environment Outlook reports of the United Nations Environment Programme (UNEP, 2002, 2007), and they appear in the standard scenario distribution set of IFs.

Software development support for modeling proceeded apace with computer hardware advances. On the systems dynamics side, support software emerged commercially with tools such as Stella in 1985 and Vensim in 1991.[3] Since World3's development, world modeling has not often used systems dynamics tools (as opposed to continued use of its concepts and logic). The Millennium Institute (founded in 1983) has, however, continued using Vensim to develop Threshold 21 (T21) as a country-based model, to augment the number of country versions of it, and to add a new iSDG version of it for study of the Sustainable Development Goals (Collste et al., 2017). At the global level, Felicjan Rydzak used Vensim to develop the FeliX (Functional Enviro-economic Linkages Integrated neXus) model at IIASA, which Brian Walsh extended and documented.[4] Although FeliX represents the world as a single unit, it is, like IFs, highly unusual in its extended, detailed, and integrated issue coverage and its availability for free download and use.

Much early modeling used scientific languages such as FORTRAN. Newer computer languages ranging from Visual BASIC to C++ became available in versions that supported object-oriented programming.[5] That made possible more modular development of the substantive blocks of models and, very importantly, the introduction into models of third-party objects that could handle menus, graphics, maps, and other features in support of sophisticated user interfaces.

Some projects have developed their own software tools and languages. For instance, the PBL Netherlands Environmental Assessment Agency has worked with MyM,[6] a visual simulation tool that has supported PBL models such as IMAGE, TIMER, GISMO, PHOENIX, and FAIR.

On the more traditional economic modeling side, a widely used modeling software tool is the General Algebraic Modeling System (GAMS), which facilitates mathematical optimization of linear and nonlinear systems across nearly all computing platforms (Lofgren et al., 2002).[7]

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[2] Work on PoleStar has effectively ceased (personal communication with Eric Kemp-Benedict, long a principal on the project, on January 17, 2016; David McAnulty of the Tellus Institute reinforced this in personal communication on January 19, 2016).

[3] See https://www.dataone.org/software-tools/stella-systems-thinking-education-and-research for Stella and http://www.ventanasystems.com/software/ for Vensim. The *Limits to Growth* project used Dynamo, still available but less used now.

[4] See http://www.felixmodel.com/; see also Walsh et al., 2015 for an example application.

[5] IFs used Visual BASIC for many years after migration from FORTRAN and expects to complete a migration to VB.NET by the end of 2019.

[6] See http://www.my-m.eu/ for the commercial spin-off of MyM. The M modeling environment and interface was originally developed with the TARGETS model (Rotmans and de Vries, 1997, p. 29).

[7] Commercially available at https://www.gams.com/. For a helpful article on GAMS, see https://en.wikipedia.org/wiki/General_Algebraic_Modeling_System.

After the emergence of GAMS in the late 1970s, enhancement of its capabilities accelerated with commercialization in the late 1980s. One of the common uses of such systems is solving the computable general equilibrium (CGE) models that economic forecasting uses widely. Another popular model support system for CGE models is the General Equilibrium Modeling PACKage (GEMPACK).[8]

Surges in data availability have also followed the early modeling work of the 1970s and supported that of later years. One example is the economic dataset that the Global Trade and Analysis Project (GTAP) has made available since its inception in 1992, including not just trade but also input-output matrices and other components of social accounting matrices. The GTAP project uses GEMPACK in its own model. GTAP's data, and sometimes its model core, support many other modeling projects, including IFs (on the data side).[9]

3.2 INTEGRATED ASSESSMENT MODELS

In combination, the advances in hardware, software, and data availability, as well as the accumulation of experience and expertise over time, support the current generation of long-term global model systems. Many of these fall into the category labeled *integrated assessment models* (IAMs), which represent various elements of the relationship between human development and the natural environment (Stehfest et al., 2014, p. 14). Although the name could appropriately identify any multiple-issue system, most models using the label pay special attention to the energy/economy/climate change nexus (see Fig. 3.1). Land use and agriculture also link to climate change as well as to water use and are additional important foci of some IAMs.

The roots of IAMs extend back to the late 1970s. Rotmans and de Vries (1997) described their early evolution, some of which focused on linkages from energy modeling to carbon emissions (Anderer et al., 1981; Nordhaus, 1979). Multiple dozens of efforts now fit into the general rubric. In 2007, the Integrated Assessment Modeling Consortium (IAMC) was established in response to the need of the Intergovernmental Panel on Climate Change for cooperative and comparative research across the efforts. In 2018, the IAMC listed 46 members, although some of them do limited or no ongoing modeling.

The analyses undertaken with IAMs explore alternative patterns of change, prescriptively focusing on reductions in environmental impacts and minimizing costs of achieving those reductions. It can be useful to begin discussion of these models through the lens of efforts that have focused heavily on using—and in the process comparing—the results of applied analysis with them, before turning to more direct structural comparison.

[8] See https://www.copsmodels.com/gempack.htm.

[9] For information on GTAP data and links to models it supports, see https://www.gtap.agecon.purdue.edu/about/data_models.asp. See https://www.gtap.agecon.purdue.edu/models/current.asp for model code download.

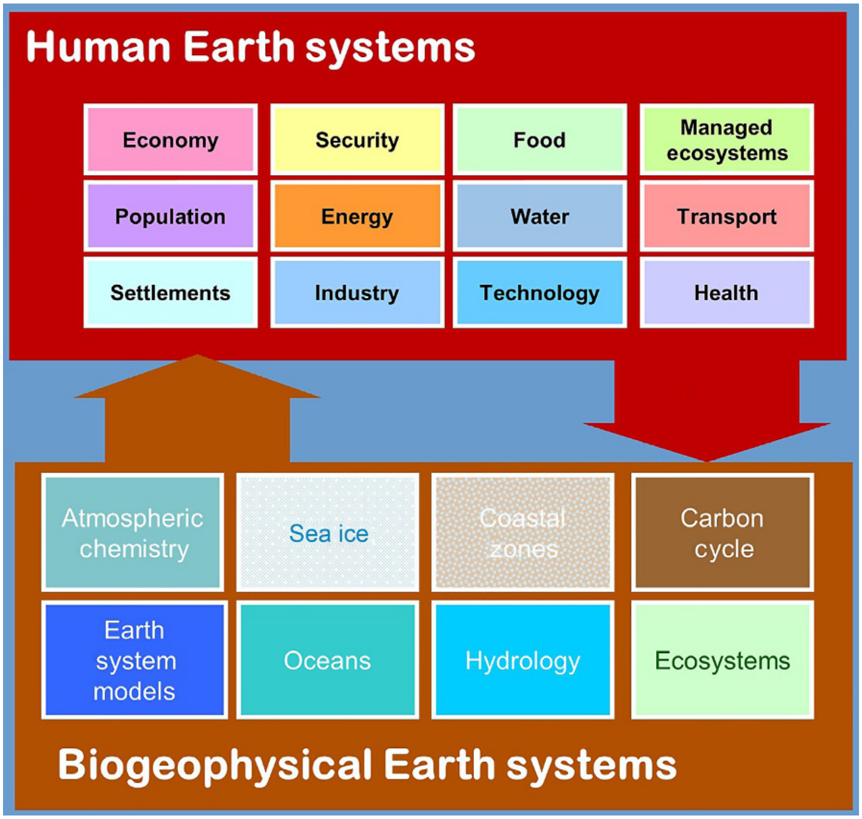

FIG. 3.1 **Integrated assessment models, potential components.**
Source: Figure created by Jae Edmonds and reproduced with permission of the Pacific Northwest National Laboratory, operating contractor of the Pacific Northwest National Laboratory for the US Department of Energy.

3.2.1 Comparative Use of IAMs[10]

One important long-term source of model comparisons is the Energy Modeling Forum (EMF) established at Stanford University in 1976. Its early efforts primarily considered the energy-economy nexus, responding to the issue of global price volatility that arose with the energy shocks of the 1970s. Within a numbered series of studies and reports, EMF-12 moved attention to analysis of global carbon emissions, looking across 14 models and 13 scenarios (Gaskins and Weyant, 1993). Many of EMF's subsequent studies have updated and extended such comparative analysis of model runs—for example, EMF-16 compared runs from 13 models in exploring the costs of the Kyoto Protocol (Weyant and Hill, 1999), and

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[10] In addition to model comparison projects using IAMs, there are comparison projects that focus on models that treat only the natural earth systems rather than also the human systems shown in Fig. 3.1 (see http://www-pcmdi.llnl.gov/projects/model_intercomparison.php). An Atmospheric Model Intercomparison Project (AMIP) has been largely folded into a Coupled Model Intercomparison Project (CMIP) that focuses on coupled ocean-atmosphere general circulation models (AOGCMS); see http://cmip-pcmdi.llnl.gov/history.html.

EMF-21 organized 19 modeling teams in an analysis of greenhouse emissions that reached beyond carbon dioxide (Weyant et al., 2006). By EMF-27, attention had expanded to 18 models and 30 scenarios in analysis across topics that included technological options for climate mitigation (such as renewable energy development, carbon capture and sequestration, and bioenergy), the implications of fossil resource availability and land-use transitions, and the impact of aerosols and short-lived greenhouse gases. The introduction by Weyant and Kriegler (2014) to the special issue of *Climatic Change* reporting on EMF-27 noted that model intercomparison had become a widespread effort globally and gave special attention to efforts in Europe.

Prominent among European efforts to compare analyses, between 2011 and 2014 the European Union financed a project in its 7th Framework Programme (FP7) for European Research and Technological Development dedicated to Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates (AMPERE). The project, which the Potsdam Institute for Climate Impact Research (PIK) coordinated, involved 22 institutions and 17 energy-economy models and IAMs, the latter adding representations of climate impact and change and also often agriculture and land use. Kriegler et al. (2015a; see also Kriegler et al., 2014 and von Stechow et al., 2016) summarized the results of comparatively using 11 of the energy-economy models and IAMs in cost-effectiveness analyses of alternative transition pathways to stabilization of greenhouse gases at the equivalent of atmospheric carbon levels at 450 or 550 ppm, with special attention to keeping global temperature rise below 2°C.[11]

The RoSE project (Roadmaps toward Sustainable Energy futures) based at PIK also undertook a major comparison of results across models, reported in a special issue of *Climatic Change*. RoSE focused on the impact of alternative assumptions about economic growth, population growth, and energy resources on energy and emissions pathways (Kriegler et al., 2016).[12]

There have been and continue to be other such projects. LIMITS (Low climate IMpact scenarios and the Implications of required Tight emission control Strategies) also ran between 2011 and 2014 and studied approaches to implementing 2°C targets.[13] Similarly, MILES (Modeling and Informing Low Emission Strategies), running from 2014 to 2017, brought many partner institutions from around the world together to elaborate low-carbon pathways.[14]

3.2.2 Comparative Assessments of IAM Structures

It is difficult to analyze the different results that models produce with respect to the same policy-related question unless we also understand the structural differences of the models themselves. Another FP7 program of the European Union sought to go beyond existing

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[11] There was a short critique by Rosen (2015) with a response by the AMPERE team (Kriegler et al., 2015b). See also https://cordis.europa.eu/project/rcn/98809_en.html and the supplemental material to the published response.

[12] See http://www.rose-project.org/.

[13] See http://www.feem-project.net/limits/01_project.html.

[14] See http://www.iddri.org/Projets/MILES-(Modelling-and-Informing-Low-Emission-Strategies).

models and to support the development of a new generation of IAMs, thus focusing its attention more sharply on model structures and capabilities. Known by the acronym ADVANCE (Advanced Model Development and Validation for Improved Analysis of Costs and Impacts of Mitigation Policies), the deliverables of the second FP7 program included enhancing model transparency across existing projects (long urged by Schneider, 1997), supporting the common use of databases and methodologies (including algorithms), and improving evaluation.

The ADVANCE project established a website that still provides documentation in common format on selected models, mostly overlapping with those used in AMPERE.[15] Structural comparison of IAMs and many other global models is not at all easy because of their size and complexity. Also documentation tends to lag behind ongoing model development (development that can produce large changes across model generations and development teams). Nonetheless, such projects and other efforts help identify several dimensions for considering general structural characteristics and variations across most existing IAM models:

- *General model type*. As described in Chapter 2, most IAMs have either dynamic recursive or intertemporal optimization forms. To reiterate, dynamic recursive models are myopic or uninformed about the future. Such models often have stock and flow elements that facilitate their movement across time. In contrast, intertemporal IAMs look across all time steps simultaneously, generally to find optimized outcomes, given specifications of constraints.[16] In general, optimization works well within a single issue or a small set of issue areas and on specific questions (e.g., what energy production mix through 2100 can satisfy consumer demand while keeping atmospheric carbon levels below 500 ppm, and subject to those and other specified constraints, also minimize costs). Such approaches are challenged when faced with a large number of goals, like simultaneously meeting several of the Sustainable Development Goals adopted by the global community across multiple issue areas.
- *Time horizon*. IAMs differ in their time horizons, with 2050 and often 2100 being more common than nearer-term horizons because of the long-term character of movement toward climate change stabilization.
- *Geographic treatment*. Geographically, IAMs most often represent the world and its regions, but regional specifications vary; individual representation of nearly all countries is rarer, especially with intertemporal optimization because of its computational intensity (models can run for hours or days).
- *Economy representation*. Economy representation of some kind is essential and almost always involves modeling equilibrium between supply and demand. Some models treat the economy as a whole or divided into a comprehensive set of sectors

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[15] See https://wiki.ucl.ac.uk/display/ADVIAM/Models. The ADVANCE project initially built on participation of 14 research institutions across Europe, but has opened the documentation website to additional IAMs, including IFs.

[16] Not all intertemporal models are driven by an objective function and pursue an optimal outcome. For instance, G-Cubed (McKibbin and Wilcoxen, 1999) uses an intertemporal structure in part to assure reasonable long-term patterns of borrowing and lending. This is an alternative to the use for the same purpose of a stock and flow structure in a recursive model like IFs.

(general equilibrium),[17] and some represent only the energy, agriculture, or other subportions of the economy (partial equilibrium).

- *Broader issue area coverage and linkage type*. By definition, IAMs represent and connect multiple issue areas with separate model characteristics, most commonly economics, energy, and the environment (especially climate change), but often also agriculture and/or land use. They differ, however, on what issue areas they cover and how they link submodels. Some linkages are hard, meaning that the computer programming physically connects models. In many IAM projects, however, so-called soft linkages, in which models are run separately and connected via data/result transfers, supplement the hard ones. In documentation and analytical reports that refer to model connections, the exact nature of linkages is not always specified.
- *Treatment of climate change*. It is unrealistic for IAMs to feed forward emission of greenhouse gases from carbon fuel burning, land-use change, and other sources via direct model linkage into the large-scale earth system models (ESMs), which include three-dimensional Atmosphere–Ocean General Circulation Models (AOGCMs) that can take days to months on supercomputers to run across 100 years. Instead, they rely on simpler representations of atmospheric (and sometimes oceanic and terrestrial) composition change and associated global warming, and it is important that they do it well (van Vuuren et al., 2011b). The most popular approach is use of models in the MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) family, a reduced-complexity model developed over more than 20 years. More recent versions include MAGICC-4 (Wigley and Raper, 2001), MAGICC/SCENGEN 5.3 (Wigley, 2008), and MAGICC 6.0.[18] Another choice is the FAIR (Finite Amplitude Impulse Response) model (Smith et al., 2018) and a third is Hector, discussed in Chapter 7. After running versions of MAGICC, FAIR, or Hector, IAMs can then feed back climate change to other variables, such as agricultural yield. Some IAMs (discussed later) integrate a still smaller set of equations representing the climate.
- *Specialized software base*. All IAMs build on various existing software/programming systems. Those using optimization generally use linear programming approaches, while general equilibrium models may use an existing economic software system such as GAMS or one developed in house. System dynamics models can use Vensim or a similar system.
- *Other special features, including technology treatment*. Depending on the model coverage, there are many other differentiations. With respect to technology, for example, models can specify advance exogenously and/or through learning by doing. At a more detailed level, possible differences are infinite.

The IAM field is so dynamic that any summary of information about specific models cannot be completely accurate. Nonetheless, the list that follows provides basic information about some of the most widely used models (most were reviewed in the AMPERE and/or ADVANCE projects). Presented alphabetically by model acronym, the subbullets identify institutional homes, general model characteristics (with some special attention to treatment of the economy), and some specialized features.

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[17] Although Kriegler et al. (2015a) characterize full economy models as general equilibrium, it would be better to characterize some of the models simply as general economy.

[18] See http://www.magicc.org.

- *AIM/CGE*: Asia-Pacific Integrated Model/Computable General Equilibrium
  - At the National Institute for Environmental Studies in Tsukuba, Japan, and collaborators
  - Recursive dynamic to 2100 with 1-year steps; 17 regions; general equilibrium across 42 sectors using GAMS/MCP (Mixed Complementary Problem software)
  - Elaborated models of energy and agriculture/land; soft link to MAGICC6 for emissions impact[19]
- *DNE21*: Dynamic New Earth 21
  - At the Research Institute of Innovative Technology for the Earth in Kyoto, Japan
  - Intertemporal optimization using linear programming; to 2050 with five-year steps to 2030 then 10-year steps; 54 regions that country breakouts can expand to 77
  - Partial equilibrium energy model without economic model and soft linked to Global Agro-Ecological Zones (GAEZ) system[20] for land/water[21]
- *GCAM*: Global Change Assessment Model
  - At the Joint Global Change Research Institute, a partnership of Pacific Northwest National Laboratory and the University of Maryland, United States.
  - Recursive dynamic to 2100 with 5-year steps (alternatively 1- or 10-year steps); 32 regions, partial equilibrium
  - Endogenous land use with 283 agro-ecological zones; extensive energy and water modeling; energy production/consumption; Hector carbon cycle and climate module[22]
- *GEM-E3*: General Equilibrium Model for Economy-Energy-Environment
  - For the European Commission, coordinated by the National Technical University of Athens with multiple partners
  - Recursive dynamic to 2050 with 5-year steps; 38 regions linked by endogenous bilateral trade; general equilibrium, including labor market, across 31 sectors using GAMS software
  - Social accounting matrix with government revenues in nine categories; no agriculture/land use[23]
- *GINFORS*: Global Inter-industry FORecasting System
  - At the Institute of Economic Structures Research (GWS), a private consulting organization in Osnabrűck, Germany with model ties to University of Osnabrűck

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[19] See http://www-iam.nies.go.jp/aim/ and https://wiki.ucl.ac.uk/display/ADVIAM/AIM-CGE.

[20] The Food and Agriculture Organization and IIASA have developed the extensive and detailed GAEZ system to provide information on climate, soil, terrain, water, and related actual and potential crop yields. Fischer et al. (2012) documented GAEZ v3.0.

[21] For information, see Sano et al., 2012. See also http://www.rite.or.jp/system/en/research/new-earth/dne21-model-outline/

[22] See www.globalchange.umd.edu/models/; see also Kim et al., 2016. The model is open source and is available at http://www.globalchange.umd.edu/gcam/download/ with documentation at http://jgcri.github.io/gcam-doc/. See also http://jgcri.github.io/gcam-doc/overview.html. Earlier was named MiniCAM.

[23] See Capros et al., 2013 at http://ftp.jrc.es/EURdoc/JRC83177.pdf for model documentation. Also see the GEM-E3 website at http://www.gem-e3.net; model.

  - Recursive dynamic to 2050; 38 countries and rest of world; economic model for 35 industries with input-output structure and bounded rationality hard-linked to trade in 59 products
  - Emissions from 28 energy carriers and global resource demand[24]
- *IFs*: International Futures
  - At the Frederick S. Pardee Center for International Futures, Josef Korbel School of International Studies, University of Denver, United States
  - Recursive dynamic to 2100 in one-year steps; 186 countries and sub-country option; general equilibrium economic model across six sectors using own software
  - Hard-linked to partial equilibrium energy and agriculture models; extensive other two-way, hard-linked models, including demographic, education, health, infrastructure and governance; simplified MAGICC calibration at country level[25]
- *IGSM*: Integrated Global System Model
  - At the Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change, United States
  - Recursive dynamic CGE from 2010 to 2100 in 5-year intervals for Economic Projection (formerly Emissions Predictions) and Policy Analysis (EPPA); an economic, energy and food consumption model; 18 global regions (version 6)
  - Intermediate complexity earth systems model using EPPA and linked to the National Center for Atmospheric Research Community Atmosphere Model (CAM), creating IGSM-CAM[26]
- *IMACLIM*: Model with a focus on the economics of decarbonization
  - Developed by Centre International de Recherche sur l'Environnement et le Développement (CIRED), France
  - Static sequential solution to 2100 in 1-year steps or recursive solution; 12 regions; general equilibrium (12 sectors); top-down economic model interacting with bottom-up energy model
  - Simplified climate model; soft link to Nexus Land-Use (NLU) model[27]
- *IMAGE*: Integrated Model to Assess the Global Environment
  - At PBL Netherlands Environmental Assessment Agency
  - Recursive dynamic to 2100 in 1- to 5-year steps; 26 regions. MAGNET from GTAP is a sector-based general equilibrium economic model, soft-linked. Simplified climate model; soft link to Nexus Land-Use (NLU) model[28]
  - Suite includes TIMER and LPJmL and various often soft-linked models dealing with biodiversity, climate change (MAGICC), climate policy, and land use.[29]

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[24] See http://www.gws-os.com/de/index.php/home.html and Meyer et al., 2013; also Lutz et al., 2006.

[25] See component model documentation reports at www.pardee.du.edu and Hughes, 2016.

[26] See https://globalchange.mit.edu/research/research-tools/global-framework; see also Chen et al., 2015, and Monier et al., 2013.

[27] See http://www2.centre-cired.fr/IMACLIM-331/?lang=en and Sassi et al., 2010.

[28] See http://www2.centris2e-cired.fr/IMACLIM-331/?lang=en and Sassi et al., 2010.

[29] IMAGE is an especially elaborated and well-documented IAM system. See http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation, and also Bouwman et al. (2006) and Stehfest et al. (2014, p. 35). For an overview of component and associated models, see http://themasites.pbl.nl/models/image/index.php/Computer_models_overview.

- *iPETS*: integrated Population-Economy-Technology-Science system
  - At the National Center for Atmospheric Research, United States
  - Computable general equilibrium economic model to 2100; nine regions across four sectors with static sequential solution
  - Exogenously prepared demographic forecasts representing households by urban/rural residence, large/small size, and household-head age; government taxes and transfers; land use; four-category energy model with carbon emissions tuned to MESSAGE (listed separately later)[30]
- *MERGE-ETL*: Model for Evaluating Regional and Global Effects of greenhouse gas reduction policies—Endogenous Technology Learning
  - At Paul Scherrer Institut, Switzerland
  - Intertemporal optimization to 2100; 10 regions; top-down, single-sector general equilibrium economic model
  - Energy drivers in production function with more elaborate bottom-up energy model; energy and other emissions model with simplified climate change representation[31]
- *MESSAGE-GLOBIOM*: Model for Energy Supply Strategy Alternatives and their General Environmental Impact—Global BIOsphere Management
  - At International Institute for Applied Systems Analysis, Austria, and International Atomic Energy Agency[32]
  - Myopic or intertemporal optimization from 1990 to 2110 in 5-year steps to 2010 then 10-year steps; 11 regions; uses MACRO (a general equilibrium economic model)[33]
  - Linear programming energy model (MESSAGE) soft linked to GLOBIOM (a land use/agriculture model), to GAINS (an air pollution model),[34] and to MAGICC; MESSAGE with GLOBIOM is the most important model set in IIASA's IAM framework
- *POLES*: Prospective Outlook on Long-term Energy Systems
  - Through the European Commission's Joint Research Centre Institutes for Prospective Technological Studies, in collaboration with the University of Grenoble EDDEN laboratory and Enerdata
  - Recursive dynamic to 2100 in 1-year steps; 66 countries and regions; partial equilibrium (exogenous GDP and demographic projections)

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[30] O'Neill et al. (2010). See also http://themasites.pbl.nl/models/advance/index.php/Reference_card_-_IPETS.

[31] Manne et al. (1995) originally developed MERGE; see http://web.stanford.edu/group/MERGE/. See also Manne and Barreto (2004) on MERGE-ETL, which has been picked up for development and use by others (see Marcucci, 2014 and Marcucci and Turton, 2012).

[32] Developed at IIASA by Wolfgang Häfele and Alan Manne.

[33] Extensive documentation is at the Advance project website: http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_MESSAGE-GLOBIOM. See also http://data.ene.iiasa.ac.at/message-globiom/index.html and Messner and Schrattenholzer, 2000.

[34] Because air pollution has such regional character, GAINS is one of few models that breaks countries into political subunits; it represents 31 provinces in China and 15 states in India. GAINS is IIASA's Greenhouse gas—Air pollution Interactions and Synergies model (see Amann, 2012 and http://www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html).

  - 15 energy demand sectors; carbon dioxide module but no land-use contribution to greenhouse emissions; Vensim software[35]
- *REMIND*: Regional Model of Investments and Development
  - At Potsdam Institute for Climate Impact Research, Germany
  - Intertemporal optimization to 2100/2150 with 5-year steps to 2050, then 10-year steps; 11 regions; general equilibrium with top-down economic model and bottom-up energy model
  - Soft linked to the MAgPIE land-use model and MAGICC6 climate model (hard-linked to reduced form model like that of DICE)[36]
- *TIAM*: TIMES Integrated Assessment Model
  - At University College, London
  - Linear optimization (but myopic possible) to 2100 in 5-year steps; 16 regions; no economic model
  - Elaborated energy model; simplified climate model based on PAGE (see entry in list below) and calibrated to MAGICC[37]
- *WITCH*: World Induced Technical Change Hybrid model
  - At Fondzione Eni Enrico Mattei (FEEM), Italy
  - Intertemporal optimization to 2150 in 5-year steps with game-theoretic set-up; 14 regions; single production sector macro-economic model
  - Hard linked to seven-sector energy model; simplified climate model calibrated to MAGICC[38]
- *WorldScan2*: Model with a focus on long-term issues in international economics
  - At the CPB Netherlands Bureau for Economic Policy Analysis, the Netherlands
  - Recursive dynamic to 2050; multi-regions; computable general equilibrium economic model
  - Extensions for specific studies, ranging from demographic aging to depletion of natural resources and the emissions of greenhouse gases[39]

Although many objectives have driven the development of these models, the ability to project the emission of greenhouse gases and their impact on global climate change has been especially common. Many systems also consider other forms of environmental damage

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[35] See http://www.enerdata.net/enerdatauk/solutions/energy-models/poles-model.php and https://ec.europa.eu/jrc/en/poles/model.

[36] On REMIND, see https://www.pik-potsdam.de/research/sustainable-solutions/models/remind/; also see Leimbach et al. (2010) and Gunner et al. (2015). On MAgPIE, see Dietrich et al. (2014) and the project Wiki at https://redmine.pik-potsdam.de/projects/magpie/wiki/Overview.

[37] See https://www.ucl.ac.uk/energy-models/models/tiam-ucl. Also see Anandarajah et al., 2011.

[38] See http://www.witchmodel.org/. Also see Bosetti et al. (2006) and Bosetti et al. (2009).

[39] See http://www.cpb.nl/en/publication/worldscan-model-international-economic-policy-analysis. Also see CPB Netherlands Bureau for Economic Policy Analysis, 1992, 1999, respectively, for an early study on scanning the future and documentation of WorldScan. See too Boeters and van Leeuwen (2010), Lejour et al. (2006), and Rojas-Romagosa (2010). Development of the WorldScan model has been less active in the last decade according to personal communication with Arjan Lejour, January 18, 2016.

(including land degradation, species extinction, and water overuse), and a few devote attention to human development and social change.

A second set of IAMs overlaps somewhat with those just discussed, but its members focus especially heavily on the damage that global warming does to human and social systems, especially the economy.

- *DICE* and *RICE*: Dynamic Integrated model of Climate and the Economy and Regional Integrated model of Climate and the Economy
  - At Yale University
  - Intertemporal optimization; 2100; DICE is global; RICE has 12 regions; macroeconomic model
  - Early versions draw heavily on FUND for estimates of total climate change impact on the economy, adding an increment for damages it does not represent; more recent releases look to a broad range of studies[40]
- *ENVISAGE*: Environmental Impact and Sustainability Applied General Equilibrium
  - At the World Bank
  - Dynamic recursive equilibrium model with multiple flexible sectors and regions based on GTAP data; exogenous population and GDP baseline with 2004–2100 horizon
  - Impact categories are agriculture productivity, sea level rise, water availability, tourism, energy demand, human health, and labor productivity[41]
- *FUND*: climate Framework for Uncertainty, Negotiation, and Distribution
  - No home base
  - Single year time steps from 1950 to 3000, to be run many times for analysis; 16 regions; exogenous population and GDP per capita scenarios (impacted)
  - Impact categories cross domains, including partial economy (agriculture), health (diseases, including malaria) and environment (forestry, sea level, storm impacts); many impacts represented as power functions of the rate or level of warming[42]
- *PAGE*: Policy Analysis of the Greenhouse Effect
  - At the University of Cambridge
  - Stochastic with 11 time steps from 2000 to 2200, to be run many times for analysis; eight regions; exogenous economy (impacted)
  - Impact categories are sea level, economic, noneconomic, and large-scale discontinuities; also considers and mitigation and adaptation costs[43]

The focus by this set of IAMs on the damages of greenhouse emissions allows the implementation of cost-benefit analyses, the major purpose of which has been to determine the social costs of carbon dioxide emissions (SCC). SCC is defined as the net present value of incremental damage from an additional ton of emissions. The SCC can guide thinking about potentially appropriate carbon taxes to compensate for those damages and reduce emissions.

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[40] See https://sites.google.com/site/williamdnordhaus/dice-rice. See also Nordhaus and Sztorc (2013) and Nordhaus (2016).

[41] See Roson and van der Mensbrugghe (2012) and van der Mensbrugghe (2010, 2013).

[42] See http://www.fund-model.org/. Also see Anthoff and Tol (2013, 2014). Model code is available at https://github.com/fund-model/fund.

[43] See Hope (2006, 2011).

The assessment of these “cost-benefit,” “social cost” (National Academies of Sciences, Engineering, and Medicine, 2017), or “policy optimization” IAMs (Weyant, 2017, p. 117 calls them “aggregate benefit-cost analysis IAMs”) focuses primarily on direct loss of GDP, but as the information about FUND and ENVISAGE suggests, can also extend to other social costs, such as damage to health (which the models also monetize). Theoretically, these models could extend the chain of causality beyond that from climate change to economic damage to include many of the human-focused Sustainable Development Goals, such as reduction of poverty and advance of education, but, at least at this point, they do not. Doing so would extend IAM modeling and analysis in the spirit of, but beyond the capability of, early world models and further link the two traditions of global modeling. As it is, Castro and Jacovkis (2015) correctly note that IAMs are heirs to world modeling more than direct descendants of it.

There have been many reviews of the models focused on cost–benefit analysis and of work done with them. For instance, the US Department of Energy sponsored the Program on Integrated Assessment Model Development, Diagnostics, and Inter-comparison (PIAMDDI)[44] under the auspices of the Energy Modeling Forum discussed earlier. (See also Ackerman et al., 2009; Anthoff and Tol, 2014; Bonen et al., 2014; Dietz and Stern, 2015; Ortiz and Markandya, 2009; Rose et al., 2017; Stanton et al., 2008; Tol, 2009; and Weitzman, 2009.)

The cost-benefit analysis effort has drawn considerable criticism. Pindyck (2015) has been concerned, for example, with the misuse of models for climate policy. Focusing especially on DICE and PAGE2002, Pindyck (2013, Abstract) argued that IAMs “have crucial flaws that make them close to useless as tools for policy analysis” because functional forms and parameter values are arbitrary, including the discount rate for future value, and because of limited knowledge about (1) climate sensitivity to CO_2 concentration, (2) the damage of temperature on GDP, and (3) the likelihood of a catastrophic climate outcome. He went on, however, to note the importance of analyzing a potentially catastrophic impact on GDP, and the approach he sketched appears vulnerable to the same general criticisms.

We can conclude that there is agreement on the importance of cost–benefit analysis—and on the need to continually improve it. Most IAMs are likely to continue to focus on cost-effectiveness of emission reduction rather than on cost–benefit analysis, but the bridge back to human systems is critically important, and Chapters 7 and 8 return to this issue.

3.3 STATUS OF AND CHALLENGES FOR GLOBAL MODEL BUILDING AND USE

The earlier emergence of the eight Millennium Development Goals (MDGs) and now the statement of 17 Sustainable Development Goals (SDGs) increasingly define the issue set of importance for global model building and use. All of the goals have associated targets that are calls for action. Coming chapters will dig much deeper into the ability of models to help address three questions around goal pursuit: (1) What path do we seem to be on relative to desired futures? (2) What leverage do we have to shift direction or accelerate progress? (3) What are the uncertainties in our understanding of our current path and our leverage? The goals and these questions shape key and highly interrelated challenges for global model development and use.

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[44] See the Powerpoint file (February 26, 2015) by John Weyant at http://science.energy.gov/∼/media/ber/berac/pdf/20150226/Weyant_BERAC_Feb_2015.pdf.

One critical challenge that the goals highlight is issue coverage and interconnection. The SDGs cut across human development, social change, and biophysical sustainability. They raise questions about the degree to which actions in goal pursuit might be competitive (e.g., for public financing), complementary (without trade-offs across the actions), and/or even synergistic (giving rise to greater total benefits when pursued together than the sum of benefits if pursued separately). Extensive issue coverage and model interconnections can potentially greatly assist such analysis.

A related challenge for model development and use is dealing with uncertainty. One element of uncertainty relates to our level of confidence in the representations of global dynamics within the models, which can be enhanced somewhat by transparency and openness of the systems. The creation of alternative scenarios tends, however, to be the primary mechanism for addressing uncertainty.

A major, widely used tool for addressing these challenges of model development and use around complexity and uncertainty involves Model Intercomparison Projects (MIPs). MIPs directly address the issues of uncertainty with respect to both structure of models and their use to study global dynamics via scenario analysis, and they exist within and increasingly across many specialized modeling areas.[45] Subsequent chapters will refer to many of them and also present comparative scenarios within and across model projects, heavily through the lens of the IFs system as introduced in Chapter 4, but also with substantial attention to other efforts.

3.3.1 Challenges in Model Building

3.3.1.1 Coverage and Connections

IAMs, by definition, do integrate models across multiple issue areas. Yet because of their heavy focus on climate change, the number of issue areas linked and the extent of interconnections are frequently limited, and often the connections are soft (nonautomated transfer of outputs from one model to another) rather than hard (fully integrated software systems).[46] For example, developers of IAMs typically have not represented population itself except via exogenous forecasts normally drawn from the United Nations or the Wittgenstein Centre for Demography and Global Human Capital in conjunction with the International Institute for Applied Systems Analysis (WIC/IIASA). In fact, of course, environmental systems have important two-way linkages with demographics. With respect to human development, education and health do not often garner much attention in IAMs except for select health implications of environmental change; again, two-way causality clearly exists. Even one of the primary connections sometimes modeled across the issue groupings of this volume,

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[45] In conversation at the Integrated Assessment Consortium meeting in Beijing in December 2016, Detlef van Vuuren suggested that there might be about 20 MIPs.

[46] Pollitt et al. (2010) reviewed 60 broadly defined integrated assessment tools focused on sustainability analysis and analyzed their coverage of 10 themes (and more specific policy areas) as defined in the EU's Sustainability Development Indicators. They found that social inclusion and governance (themes included in IFs treatment of social development) were least well covered (2010: 40–43). The models also gave only limited endogenous attention to demographics and health, even though those are key issues within human development.

namely the impact of environmental change on the economy, has been difficult to build and remains subject to significant controversy. With respect to climate change itself, IAMs do not include hard linkages with full-scale atmosphere-ocean general circulation models because of the complexity and computation demands of GCMs; instead, as we have discussed, they rely on simpler models like MAGICC or small sets of equations.

There are important explanations for somewhat restricted issue foci in IAMs and for the potentially limited connectivity of those represented. In support of the IPCC's fifth assessment round, Clarke and Jiang (2014) surveyed existing studies and the range of opportunities for building analysis of broad developmental objectives like the MDGs into climate analysis. The authors emphasized the complications of doing so, given factors such as the difficulties of putting multiple objectives that may be extremely difficult to compare (such as relieving energy poverty, improving health, and avoiding species loss) into a common welfare metric. The frequent use within IAMs of intertemporal optimization to identify policy recommendations also complicates analysis of multiple goals in different issue areas; as discussed earlier, the specification of objectives to optimize tends to narrow the focus to one or a small set of goals rather than to facilitate analysis of many simultaneously.

Among the more traditional IAMs with heavy emphasis on sustainability issues, the IMAGE suite introduced in Section 3.2.2 is one system that stands out in the extent of its broad hard-linked and soft-linked connections. IMAGE benefitted in its early versions from work done at the National Institute of Public Health and the Environment on the TARGETS model (Tool to Assess Regional and Global Environmental and health Targets for Sustainability), no longer in use. It also fed development of TARGETS with population and health, energy, land and food, water, and biochemical submodels (see Rotmans and de Vries, 1997, p. 38; Rotmans et al., 1994; van Asselt and Rotmans, 1995). Interestingly, work on TARGETS explicitly looked to the earlier world modeling tradition as well as to the emergence of IAMs. That approach facilitated inclusion of bidirectional linkages between human and environmental systems, even representing elements of the World3 population and natural resource modeling (Rotmans et al., 1994, p. 29), including feedbacks from environmental and health variables to population. TARGETS also sought to represent cultural perspectives in the system.

The philosophy of the TARGETS system also influenced GISMO (Global Integrated Sustainability Model), also at the PBL Netherlands Environmental Assessment Agency as a component of the IMAGE suite. Similarly, the philosophy of linking across human, social, and environmental systems more comprehensively, thereby cutting across the earlier world modeling and later integrated assessment modeling traditions, influenced FeliX (at IIASA) and IFs (see Chapter 4). Analysis of the SDGs benefits greatly from being at a fairly disaggregated level geographically. FeliX represents the world as a whole, a trade-off with its issue-area extensiveness; GISMO represents 27 world regions (as does IMAGE) and IFs represents 186 countries.

3.3.1.2 Transparency and Openness

Simpler can sometimes be better in modeling; for example, it can facilitate focus on a small set of issues and questions. Yet the rise of attention to the Sustainable Development Goals with their broad issue coverage reinforces recognition that simpler can also be misleading. For that reason, this volume urges more rather than fewer model interconnections.

Unfortunately, however, extensive issue coverage and connection can lessen transparency concerning the analytical basis for model outputs, another feature that we want to see. To be useful and credible either in describing the path we seem to be on or exploring leverage, models need to be understandable by experts and policy makers and even a broader educated public.

How transparent in character and open for others to use are IAMs? Documentation invariably runs behind model development, often quite dramatically so. The code of most global models never leaves the computers of their developers. Thus even modelers often have a difficult time understanding the structures of other systems (or their own, as new generations of modelers take over systems that others developed). The field needs clear identification of at least the most important structures and formulations (equations and algorithms) in the models, as the ADVANCE project website is now increasingly doing, and analysis of the consequences of variations in them.

With respect to openness, some modelers assert that their tools should not be available for use by others because those others will not understand the models and use them appropriately. That argument has basis, but lack of openness raises both political and practical issues. On the political side, it can make global modeling appear to be a closed, elite activity, thereby giving rise to skepticism about its findings. On the practical side, not being open can limit potentially very useful review and feedback. In addition to its emphasis on models across multiple issue areas like those encompassed by the SDGs, this volume argues that (1) more attention to documentation is critical, not only for those outside of projects but for the new generations of modelers who join ongoing efforts, and that (2) efforts should be made to extend access to use of models whenever possible. The GCAM project has illustrated one approach to this by utilizing the GitHub system for collaborative work on both its documentation and model code.[47]

3.3.2 Challenges in Model Use: Dealing With Uncertainty

Building on modeling coverage of multiple issue areas, integration of models via soft and hard linkages, and significant understanding of the resulting systems, it is possible to move to the challenge of analysis and better understanding, and even shaping, of alternative possible futures, the central goals of the global modeling enterprise. Doing so, however, raises the critical challenge of addressing uncertainty.

One element of uncertainty relates to our level of confidence in the representations of global dynamics within the models; it can be reduced somewhat by transparency as well as by ability to explore the sensitivity of projections to alternative structures and parameters. Another element of uncertainty lies in human agency and other global forces that will shift patterns of change and be disruptive (for better and worse) in many ways that we cannot anticipate; while much of even transformative change will be gradual, many dramatic changes have characterized world history and will continue to do so.[48]

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[47] See https://github.com/JGCRI.

[48] PAGE does include a representation of economic consequences of discontinuous impacts of temperature change, such as the melting of the Greenland ice sheet (Hope, 2011, p. 8 in unpaginated document). Lenton et al. (2008) identified possible climate system tipping points, ranking the melting of Artic sea ice and the Greenland ice sheet as the greatest threats.

As noted earlier, the Model Intercomparison Projects facilitate comparison of both model structures and their projections. Much of their attention has been on the development and testing of scenarios. An important example is the Coupled Model Intercomparison Project (CMIP). The early phases of the CMIP focused on collecting and sharing output from climate models. More recent phases have interacted strongly with the development of scenarios and have extended issue area focus. For instance, Phase 3 (CMIP3) drew on a set of climate change scenarios developed under the leadership of Nakićenović and presented in the IPCC Special Report on Emissions Scenarios (IPCC, 2000). Those scenarios preceded the development of another set called representative concentration pathways (RCPs) that define alternative climate change futures in terms of the radiative forcing of rising atmospheric greenhouse gas accumulations (van Vuuren et al., 2011a). The original set of RCPs (discussed further in Chapter 7) identified increases of forcing in 2100 of 2.6, 4.5, 6.0, and 8.5 watts per square meter relative to pre-industrial values and named the scenarios for those values. CMIP5 used the RCPs in its work on connecting IAMs with large-scale climate models.[49]

The early work of the CMIP was heavily focused on climate models and understanding climate change.[50] Starting with CMIP6, however, the issue area focus has broadened and interconnections are becoming stronger. The primary activity of CMIP6 is the Scenario Model Intercomparison Project (ScenarioMIP), which builds on the shared socioeconomic pathway scenarios (SSPs, discussed in the next section), connecting those also with the RCPs (O'Neill et al., 2016). This effort is facilitating the connection of analysis from the climate science, IAM, and IAV (impacts, adaptation, and vulnerability) communities. In the process, the original RCPs and the shared socioeconomic pathways are being extended and mapped against each other, considerably broadening model use and influencing further model development.

3.3.2.1 Shared Socioeconomic Pathways (SSPs)

The SSPs, developed in conjunction with the IPCC process, come from an important scenario process intended to help identify and map uncertainties and options around mitigation of environmental change (via reduction of greenhouse gas emissions) and adaptation to it. The use of fossil fuels and changes in land use are important direct determinants of human environmental impact (for instance, via radiative forcing from accumulated greenhouse gases and resultant change in global temperatures). Yet, it is difficult to elaborate processes of mitigation and/or adaptation without more extended attention to human systems (Moss et al., 2010; Nakićenović et al., 2014; van Vuuren et al., 2014). The SSP process, involving a large informal community of researchers globally, began with the elaboration of five qualitative scenarios (see Fig. 3.2) about variations in socioeconomic systems that would collectively shape pathways with variable implications for mitigation and adaptation (Kriegler et al., 2012; O'Neill et al., 2017, 2014).

Drawing on multiple models, the SSP community initially generated national-level projections of key socioeconomic variables that help manifest the five stories: population in total, and by age and sex, and adult average education level from WIC/IIASA; urbanization level

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[49] See CMIP web sites at http://cmip-pcmdi.llnl.gov/ and https://cmip.ucar.edu/.

[50] Another important MIP, the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), initiated by PIK and IIASA and now very extensive, works via rounds of simulations to compare model analyses of impact from different levels of climate change on a wide range of mostly biophysical systems. See https://www.isimip.org/about/.

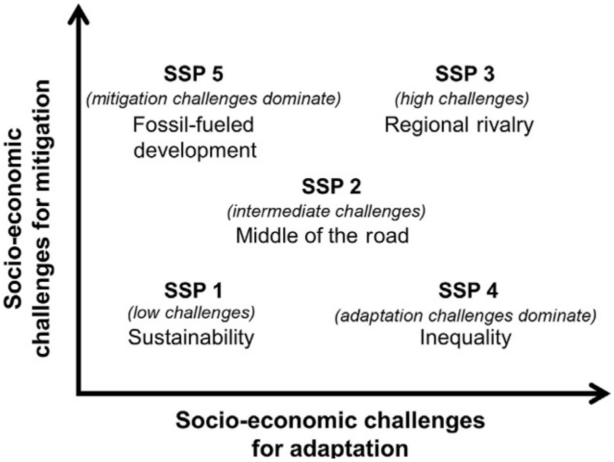

FIG. 3.2 **Shared socioeconomic pathway scenario space and scenarios.**
Source: Fig. 1 (p. 170) from O'Neill, B.C. et al., 2017. The roads ahead: narratives for shared socio-economic pathways describing world futures in the 21st century. Global Environ. Change 42 (January), 169–180. DOI:https://doi.org/10.1016/j.gloenvcha.2015.01.004.

from the National Center for Atmospheric Research; and GDP from the Organisation for Economic Co-operation and Development, PIK, and IIASA. In further work, teams using six integrated assessment models have taken those quantifications of the SSP-defining socioeconomic variables and generated projections of associated variables driving environmental change, such as land use, energy production and consumption, and greenhouse gas emissions (Riahi et al., 2017). Those projections were often initially at the level of global regions rather than individual countries.

The six IAMs used for elaborating the SSPs are AIM/CGE, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MagPIE, and WITCH-GLOBIOM (see information about them earlier in the chapter). All six developed projections for SSP1 and SSP2 and at least one other SSP scenario; in combination, all SSP scenarios were covered (see Riahi et al., 2017, p. 156 [Table 1]).[51] The results of a single IAM were identified as a "marker" or representative scenario for each of the SSPs (see Bauer et al., 2017). However, because all six IAMs replicated SSP1 and SSP2 (the Sustainability and Middle-of-the-Road scenarios), broad comparison of projections for those scenarios across models provides some indication of ranges of uncertainty even within scenarios. Similarly, since multiple models generated versions of the other SSPs, those too can be compared with the relevant marker scenario, framing uncertainty broadly. Planned future steps involve geographical and sectoral elaborations and use of the SSP scenarios with new earth system models.

One of the challenges for the extension of SSPs to emissions and land-use scenarios was the difficulty of associating the representation of assumptions about mitigation that help shape the SSPs with the set of RCP scenarios widely used in the IPCC process to represent the driving of climate change by atmospheric greenhouse gas accumulation. Riahi et al. (2017, Fig. 5, p. 162)

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[51] See "Supplementary Note for the SSP Data Set," available at https://tntcat.iiasa.ac.at/SspDb/static/download/ssp_suplementary%20text.pdf. IIASA maintains the database for SSP projections at https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about and provides information on models and methods (IIASA, 2015).

showed that the lowest radiative forcing across marker scenarios is from SSP1 (Sustainability scenario) and is slightly closer to RCP6.0 than RCP4.5 in 2100; SSP5 (Fossil-fueled Development) pushes the level above RCP8.5. Even the SSP2 (Middle-of-the-Road) marker scenario produces levels well above RCP6.0. CMIP6 has elaborated additional variations of both SSPs and RCPs to help connect them more strongly (O'Neill et al., 2016).

Those involved in the SSP process face a number of other challenges that take us back again to modeling limitations, including issue coverage and integration. First, projections of the selected core socioeconomic variables (population, education, urbanization, and GDP) representing the five scenarios come from different models and are not necessarily fully consistent (Jiang, 2014). Second, human and social system representation in IAMs typically does not include other important variables that would also affect, or be affected by, mitigation and adaptation in the SSPs, such as poverty, inequality, and governance (including governance quality and the financial capabilities of government). Third, and for the same reason—that human and social system representation is limited—IAMs are challenged in feeding back environmental change to those systems. It is striking, for example, that IAMs almost without exception still rely on exogenous population forecasts and often do not represent the impacts of environmental change on education or life expectancy. See Carleton and Hsiang, 2016 for a synopsis of what studies in the IAM community do identify as broad social and economic impacts of climate change, even if models do not yet represent the full range of those impacts; Chapter 8 returns to the topic.

The integration of problem agendas in the SDGs and the emergent SSP focus of IAMs might constructively lead to some shift "back to the future"—namely, a renewed attention to the broader two-way integration of human and physical systems that characterized early world modeling. If soft linking of models greatly complicates model analysis and hard linking of them across all issue areas is unwieldly, perhaps one alternative approach in the longer term could be creation of plug-and-play capabilities to link models (also with flexible formulation substitution) needed for issue-specific analysis.

As Chapters 5–7 elaborate model structures and development across many specific issue areas, they will present projections associated with the SSPs. Those projections will allow both a mapping of the range of uncertainty in those issue areas and a comparison with projections from IFs.

3.3.2.2 *Other Integrative Analytical Initiatives*

Picking up on the need and the opportunities for using multiple models and scenarios to explore a range of developmental issues and associated goals, the CD-LINKS project (Linking Climate and Development Policies—Leveraging International Networks and Knowledge Sharing) is an effort to identify, extend, and use the potential contributions of many IAMs in analysis of the SDG process and progress. It was established in September 2015, with 19 partners and collaborators around the world and an initial time horizon until August 2019.[52]

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[52] See http://www.cd-links.org/.

Another integrative project is The World in 2050 (TWI2050), with preparatory workshops in 2015 and 2016.[53] IIASA (the home of the project secretariat), the Sustainable Development Solutions Network, and the Stockholm Resilience Center launched this initiative. TWI2050 is explicitly interested in understanding the transformational challenges and potential synergies in pursuit of the 17 SDGs.

3.4 FINAL COMMENTS ON GLOBAL MODEL EVOLUTION AND CHALLENGES

The history of global modeling now reaches back nearly 50 years. The advances over that time cannot fail to impress anyone familiar with the early efforts. Building on tremendous improvements in data, computing capabilities, software support systems, and ongoing work by others, model builders have created sophisticated new tools and analyses. Coverage of important issue areas and integration of them remain ongoing challenges, as do transparency and openness and the treatment of uncertainty, including major disruptions. We will never be, nor should we ever be, completely satisfied with our models.

The next chapters focus on further exploration of model structures, behavior, and analysis. That exploration begins with an overview of the International Futures model system, both because of the author's involvement with it and because it spans the three issue sets of global goals—namely, human development, social change, and biophysical sustainability.

References

Ackerman, F., DeCanio, S.J., Howarth, R.B., Sheeran, K., 2009. Limitations of integrated assessment models of climate change. Clim. Chang. 95 (3–4), 297–315. https://dx.doi.org/10.1007/s10584-009-9570-x.

Amann, M. (Ed.), 2012. The GAINS Integrated Assessment Model. EC4MACS Modelling Methodology. European Consortium for Modelling of Air Pollution and Climate Strategies. IIASA, Laxenburg, Austria. http://www.ec4macs.eu/content/report/EC4MACS_Publications/MR_Final%20in%20pdfEC4MACS/GAINS_Methodologies_Final.pdf.

Anandarajah, G., Pye, S., Usher, W., Kesicki, F., Mcglade, C., 2011. TIAM-UCL Global Model Documentation. UK Energy Research Centre Working Paper UKERC/WP/ESY/2011/001. University College, London, UK. https://www.ucl.ac.uk/energy-models/models/tiam-ucl/tiam-ucl-manual.

Anderer, J., McDonald, A., Nakićenović, N., 1981. Energy in a Finite World: Paths to a Sustainable Future. Report by the Energy Systems Program Group of the International Institute for Applied Systems Analysis. Ballinger, Cambridge, MA.

Anthoff, D., Tol, R.S.J., 2013. The uncertainty about the social cost of carbon: a decomposition analysis using FUND. Clim. Chang. 117 (3), 515–530. https://dx.doi.org/10.1007/s10584-013-0706-7.

Anthoff, D., Tol, R.S.J., 2014. The Climate Framework for Uncertainty, Negotiation and Distribution (FUND): Technical Description, Version 3.9. Use FUND 3.9 Documentation download option from, http://www.fund-model.org/versions.

Ball, R.J. (Ed.), 1973. International Linkage of National Economic Models. Elsevier North-Holland, Amsterdam, the Netherlands.

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., et al., 2017. Shared socio-economic pathways of the energy sector—quantifying the narratives. Glob. Environ. Chang. 42 (January), 316–330. https://dx.doi.org/10.1016/j.gloenvcha.2016.07.006.

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[53] See http://www.iiasa.ac.at/web/home/research/twi/TWI2050.html.

Boeters, S., van Leeuwen, N., 2010. A Labour Market Extension for WorldScan Modelling Labour Supply, Wage Bargaining and Unemployment in a CGE Framework. CPB Document no. 201. CPB Netherlands Bureau for Economic Policy Analysis, The Hague, the Netherlands. http://www.cpb.nl/zoek?keys=Worldscan.

Bonen, A., Semmler, W., Klasen, S., 2014. Economic Damages from Climate Change: A Review of Modeling Approaches. Working Paper no. 2014-3. Schwartz Center for Economic Policy Analysis, The New School for Social Research, New York, NY.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2006. WITCH: a world induced technical change hybrid model. Energy J. 27 (Special Issue—Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down), 13–38. http://www.jstor.org.du.idm.oclc.org/stable/23297044.

Bosetti, V., Tavoni, M., De Cian, E., Sgobbi, A., 2009. The 2008 WITCH Model: New Model Features and Baseline. FEEM Working Paper 85.2009. Fondazione Eni Enrico Mattei, Venezia, Italy. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1512475.

Bouwman, A.F., Kram, T., Klein Goldewijk, K. (Eds.), 2006. Integrated Modelling of Global Environmental Change—An Overview of IMAGE 2.4. MNP publication number 500110002/2006. Netherlands Environmental Agency (MNP), Bilthoven, the Netherlands. http://www.pbl.nl/sites/default/files/cms/publicaties/500110002.pdf.

Brecke, P., 1990. A bibliographical report on six contemporary world models. In: Chestnut, H., Kopacek, P., Vámos, T. (Eds.), International Conflict Resolution Using System Engineering. Proceedings of the IFAC Workshop, Budapest, Hungary, 5–8 June 1989. Pergamon Press, Oxford, UK, pp. 93–112.

Bremer, S.A. (Ed.), 1987. The GLOBUS Model: Computer Simulation of Worldwide Political and Economic Developments. Westview Press, Boulder, CO.

Capros, P., van Regemorter, D., Paroussos, L., Karkatsoulis, P., 2013. GEM-E3 Model Documentation. European Commission Joint Research Centre Technical Report EUR 26034 EN. Publications Office of the European Union, Luxembourg. ftp://ftp.jrc.es/pub/EURdoc/JRC83177.pdf.

Carleton, T.A., Hsiang, S.M., 2016. Social and economic impacts of climate. Science 353 (6304), aad9837. https://dx.doi.org/10.1126/science.aad9837.

Castro, R., Jacovkis, P.M., 2015. Computer-based global models: from early experiences to complex systems. J. Artif. Soc. Soc. Simulat. 18(1). https://dx.doi.org/10.18564/jasss.2651.

Cazalet, E.G., Stanford Research Institute, 1977. Generalized Equilibrium Modeling: The Methodology of the SRI-Gulf Energy Model. Final Report. Decision Focus Inc. and Stanford Research Institute, Palo Alto and Menlo Park, CA. http://www.cazalet.com/images/GEMS-1977.pdf.

Chen, Y.-H.H., Paltsey, S., Reilly, J.M., Morris, J.F., Babiker, M.H., 2015. The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. MIT Joint Program on the Science and Policy of Global Change Report no. 278. Massachusetts Institute of Technology, Cambridge, MA. https://globalchange.mit.edu/sites/default/files/MITJPSPGC_Rpt278.pdf.

Clarke, L., Jiang, K., 2014. Assessing transformation pathways. In: Intergovernmental Panel on Climate Change, Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report. Cambridge University Press, New York, NY, pp. 413–510.

Cole, H.S.D., 1977. Global Models and the International Economic Order. Pergamon Press, Oxford, UK.

Collste, D., Pedercini, M., Cornell, S.E., 2017. Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies. Sustain. Sci. 12 (6), 921–931. https://dx.doi.org/10.1007/s11625-017-0457-x.

CPB Netherlands Bureau for Economic Policy Analysis, 1992. Scanning the Future: A Long-Term Scenario Study of the World Economy 1990-2015. CPB Special Publication 1. Sdu, The Hague, the Netherlands.

CPB Netherlands Bureau for Economic Policy Analysis, 1999. WorldScan: The Core Version. CPB Special Publication 20. CPB Netherlands Bureau for Economic Policy Analysis, The Hague, the Netherlands. https://www.cpb.nl/sites/default/files/publicaties/download/worldscan-core-version.pdf.

Deardorff, A.V., Stern, R.M., 1986. The Michigan Model of World Production and Trade: Theory and Applications. MIT Press, Cambridge, MA.

Dietrich, J.P., Schmitz, C., Lotze-Campen, H., Popp, A., Müller, C., 2014. Forecasting technological change in agriculture—an endogenous implementation in a global land use model. Technol. Forecast. Soc. Chang. 81 (January), 236–249. https://dx.doi.org/10.1016/j.techfore.2013.02.003.

Dietz, S., Stern, N., 2015. Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. Econ. J. 125 (583), 574–620. https://dx.doi.org/10.1111/ecoj.12188.

Electris, C., Raskin, P., Rosen, R., Stutz, J., 2015. The Century Ahead: Four Global Scenarios. Technical Documentation. Tellus Institute, Boston, MA. (originally 2009). http://www.tellus.org/pub/The_Century_Ahead_-_Four_Global_Scenarios_-_Technical_Documentation.pdf.

Fischer, G., Nachtergaele, F.O., Prieler, S., Teixeira, E., Tóth, G., van Velthuizen, H., et al., 2012. Global Agro-Ecological Zones (GAEZ v3.0): Model Documentation. International Institute for Applied Systems Analysis, and Food and Agriculture Organization, Laxenburg, Austria, and Rome, Italy. http://www.fao.org/fileadmin/user_upload/gaez/docs/GAEZ_Model_Documentation.pdf.

Forrester, J.W., 1968. Principles of Systems. Wright-Allen Press, Cambridge, MA.

Forrester, J.W., 1971. World Dynamics. Wright-Allen Press, Cambridge, MA.

Gaskins Jr., D.W., Weyant, J.P., 1993. Model comparisons of the costs of reducing CO2 emissions. Am. Econ. Rev. 83 (2), 318–323. http://www.jstor.org.du.idm.oclc.org/stable/2117684.

Gunner, L., Leimbach, M., Bauer, N., Kriegler, E., Baumstark, L., Bertram, C., et al., 2015. Description of the REMIND Model (Version 1.6). Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany. https://www.pik-potsdam.de/research/sustainable-solutions/research/global-energy-systems/remind16_description_2015_11_30_final.

Herrera, A.O., Scolnik, H.D., Chichilnisky, G., Gallopin, G.C., Hardoy, J.E., Mosovich, D., et al., 1976. Catastrophe or New Society? A Latin American World Model. IDRC Report 064e. International Development Research Centre, Ottawa, ON, Canada.

Hickman, B.G. (Ed.), 1983. Global International Economic Models: Selected Papers from an IIASA Conference. Elsevier Science Publishers, Amsterdam, the Netherlands.

Hicks, N.L., 1975. The Simlink Model of Trade and Growth for the Developing World. WB Staff Working Paper No. 220. World Bank, Washington, DC. http://documents.worldbank.org/curated/en/677071468173350959/pdf/SWP220000The0s0the0developing0world.pdf.

Hope, C., 2006. The marginal impact of CO2 from PAGE2002: an integrated assessment model incorporating the IPCC's five reasons for concern. Integr. Assess. J. 6 (1), 16–56. http://journals.sfu.ca/int_assess/index.php/iaj/article/view/227/190.

Hope, C., 2011. The PAGE09 Integrated Assessment Model: A Technical Description. Cambridge Judge Business School Working Paper Series 4/2011. University of Cambridge, Cambridge, UK. https://www.jbs.cam.ac.uk/fileadmin/user_upload/research/workingpapers/wp1104.pdf.

Hughes, B.B., 1980. World Modeling: The Mesarovic-Pestel World Model in the Context of Its Contemporaries. Lexington Books, Lexington, MA.

Hughes, B.B., 1985. World models: the bases of difference. Int. Stud. Q. 29 (1), 77–101. https://dx.doi.org/10.2307/2600480.

Hughes, B.B., 2016. International Futures (IFs) and integrated, long-term forecasting of global transformations. Futures 81 (August), 98–118. https://dx.doi.org/10.1016/j.futures.2015.07.007.

Intergovernmental Panel on Climate Change (IPCC), 2000. Emissions scenarios: summary for policymakers. In: IPCC Working Group III Special Report. IPCC Secretariat, Geneva, Switzerland. https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf.

International Institute for Applied Systems Analysis (IIASA), 1977. MOIRA: Food and Agriculture Model. Proceedings of the Third IIASA Symposium on Global Modeling, September 22–25, 1975. International Institute for Applied Systems Analysis, Laxenburg, Austria.

International Institute for Applied Systems Analysis (IIASA), 2015. Model Description. Unpublished overview of the six models that had then participated in the development of the SSP scenarios. International Institute for Applied Systems Analysis, Laxenburg, Austria. https://tntcat.iiasa.ac.at/SspDb/download/iam_scenario_doc/SSP_Model_Documentation.pdf.

Jiang, L., 2014. Internal consistency of demographic assumptions in the shared socioeconomic pathways. Popul. Environ. 35 (3), 261–285. https://dx.doi.org/10.1007/s11111-014-0206-3.

Kim, S.H., Hejazi, M., Liu, L., Calvin, K., Clarke, L., Edmonds, J., et al., 2016. Balancing global water availability and use at basin scale in an integrated assessment model. Clim. Chang. 136 (2), 217–231. https://dx.doi.org/10.1007/s10584-016-1604-6.

Klein, L.R., Su, V., 1979. Protectionism: an analysis from project LINK. J. Policy Model 1 (1), 5–35. https://dx.doi.org/10.1016/0161-8938(79)90042-5.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. Glob. Environ. Chang. 22 (4), 807–822. https://dx.doi.org/10.1016/j.gloenvcha.2012.05.005.

Kriegler, E., Riahi, K., Petermann, N., Bosetti, V., Capros, P., van Vuuren, D.P., et al., 2014. Assessing Pathways toward Ambitious Climate Targets at the Global and European Levels: A Synthesis of Results from the AMPERE Project. AMPERE Consortium. Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany. http://ampere-project.eu/web/images/Final_Conference/ampere_synthesis_5-2014-compact.pdf.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V.J., Petermann, N., Bosetti, V., et al., 2015a. Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. Technol. Forecast. Soc. Chang. 90 (Part A), 24–44. https://dx.doi.org/10.1016/j.techfore.2013.09.021.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V.J., Petermann, N., Bosetti, V., et al., 2015b. A short note on integrated assessment modeling approaches: rejoinder to the review of 'making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy.' Technol. Forecast. Soc. Chang. 99 (October), 273–276. https://dx.doi.org/10.1016/j.techfore.2015.07.011.

Kriegler, E., Mouratiadou, I., Luderer, G., Edmonds, J., Edenhofer, O., 2016. Introduction to the RoSE special issue on the impact of economic growth and fossil fuel availability on climate protection. Clim. Chang. 136 (1), 1–6. https://dx.doi.org/10.1007/s10584-016-1667-4.

Lee, H., Oliveira Martins, J., van der Mensbrugghe, D., 1994. The OECD Green Model: An Updated Overview. OECD Development Centre Working Paper no. 97. Organisation for Economic Co-operation and Development Publishing, Paris, France.

Leimbach, M., Bauer, N., Baumstark, L., Lüken, M., Edenhofer, O., 2010. Technological change and international trade: insights from REMIND-R. Energy J. 31, 109–136. Special Issue 1. http://www.jstor.org.du.idm.oclc.org/stable/41323493.

Lejour, A., Veenendaal, P., Verweij, G., van Leeuwen, N., 2006. WorldScan: A Model for International Economic Policy Analysis. CPB Document no. 111. Netherlands Bureau for Economic Policy Analysis, The Hague, the Netherlands. http://www.cpb.nl/en/publication/worldscan-model-international-economic-policy-analysis.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. U. S. A. 105 (6), 1786–1793.

Leontief, W., Carter, A., Petri, P., 1977. The Future of the World Economy. Oxford University Press, New York, NY.

Lofgren, H., Harris, R.L., Robinson, S., 2002. A Standard Computable General Equilibrium (CGE) Model in GAMS. Microcomputers in Policy Research 5 (Manual). International Food Policy Research Institute, Washington, DC. http://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/74845/filename/74846.pdf.

Lutz, C., Meyer, B., Wolter, M.I., Giljum, S., 2006. The GINFORS Model in the MOSUS Project: Model Description and Baseline Projection. Department of Economics and Business Administration, University of Osnabruck, Osnabrück, Germany. http://userpage.fu-berlin.de/ffu/akumwelt/bc2006/papers/Lutz_GINFORS.pdf.

Manne, A.S., Barreto, L., 2004. Learn-by-doing and carbon dioxide abatement. Energy Econ. 26 (4), 621–633. https://dx.doi.org/10.1016/j.eneco.2004.04.023.

Manne, A., Mendelsohn, R., Richels, R., 1995. MERGE: a model for evaluating regional and global effects of GHG reduction policies. Energy Policy 23 (1), 17–34. https://dx.doi.org/10.1016/0301-4215(95)90763-W.

Marcucci, A., 2014. The MERGE-ETL Model: 2014 Assumptions and Model Calibration. Paul Scherrer Institute (PSI), Villigen, Switzerland. https://www.psi.ch/eem/ModelsEN/2014MergeCalibration.pdf.

Marcucci, A., Turton, H., 2012. The MERGE-ETL Model: Model Documentation. Paul Scherrer Institute (PSI), Villigen, Switzerland. https://www.psi.ch/eem/ModelsEN/2012MergeDescription.pdf.

McKibbin, W.J., Wilcoxen, P.J., 1999. The theoretical and empirical structure of the G-cubed model. Econ. Model. 16 (1), 123–148. https://dx.doi.org/10.1016/S0264-9993(98)00035-2.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens III, W.W., 1972. Limits to Growth. Universe Books, New York, NY.

Meadows, D.H., Richardson, J., Bruckmann, G., 1982. Groping in the Dark: The First Decade of Global Modelling. John Wiley & Sons, New York, NY.

Meadows, D.H., Meadows, D.L., Randers, J., 1992. Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future. Chelsea Green, White River Junction, VT.

Meadows, D.L., Behrens III, W.W., Meadows, D.H., Naill, R.F., Randers, J., Zahn, E.K.O., 1974. Dynamics of Growth in a Finite World. Wright-Allen Press, Cambridge, MA.

Mesarovic, M.D., Pestel, E., 1974a. Mankind at the Turning Point. E. P. Dutton & Co, New York, NY.

Mesarovic, M.D., Pestel, E. (Eds.), 1974b. Multilevel Computer Model of World Development System. Vols. 1–6. Extracts From Symposium Proceedings, Laxenburg, Austria, April 29–May 3, 1974. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Messner, S., Schrattenholzer, L., 2000. MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy 25 (3), 267–282. https://dx.doi.org/10.1016/S0360-5442(99)00063-8.

Meyer, M., Distelkamp, M., Ahlert, G., Meyer, B., 2013. Macroeconomic Modelling of the Global Economy-Energy-Environment Nexus: An Overview of the Recent Advancements of the Dynamic Simulation Model GINFORS. GWS Discussion Paper 2013/5. The Institute of Economic Structures Research (GWS), Osnabrűck, Germany. http://www.rug.nl/ggdc/docs/session3_meyer_paper.pdf.

Monier, E., Scott, J.R., Sokolov, A.P., Forest, C.E., Adam Schlosser, C., 2013. An integrated assessment modeling framework for uncertainty studies in global and regional climate change: the MIT IGSM-CAM (version 1.0). Geosci. Model Dev. 6 (6), 2063–2085. https://dx.doi.org/10.5194/gmd-6-2063-2013.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463 (7282), 747–756. https://dx.doi.org/10.1038/nature08823.

Nakićenović, N., Lempert, R.J., Janetos, A.C., 2014. A framework for the development of new socio-economic scenarios for climate change research: introductory essay. Clim. Chang. 122 (3), 351–361. https://dx.doi.org/10.1007/s10584-013-0982-2.

National Academies of Sciences, Engineering, and Medicine, 2017. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. National Academies Press, Washington, DC. https://dx.doi.org/10.17226/24651.

Nordhaus, W.D., 1979. The Efficient Use of Energy Resources. Yale University Press, New Haven, CT.

Nordhaus, W.D., 2016. Projections and Uncertainties About Climate Change in an Era of Minimal Climate Policies. Cowles Foundation Discussion Paper no. 2057. Cowles Foundation for Research in Economics, Yale University, New Haven, CT. http://cowles.yale.edu/sites/default/files/files/pub/d20/d2057.pdf.

Nordhaus, W., Sztorc, P., 2013. DICE 2013R: Introduction and User's Manual. Department of Economics, Yale University, New Haven, CT. http://www.econ.yale.edu/~nordhaus/homepage/documents/DICE_Manual_103113r2.pdf.

O'Neill, B.C., Dalton, M., Fuchs, R., Jiang, L., Pachauri, S., Zigova, K., 2010. Global demographic trends and future carbon emissions. Proc. Natl. Acad. Sci. U. S. A. 107 (31), 17521–17526. https://dx.doi.org/10.1073/pnas.1004581107.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., et al., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Chang. 122 (3), 387–400. https://dx.doi.org/10.1007/s10584-013-0905-2.

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., et al., 2016. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci. Model Dev. 9 (9), 3461–3482.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., et al., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42 (January), 169–180. https://dx.doi.org/10.1016/j.gloenvcha.2015.01.004.

Onishi, A., 2001. Integrated global models of sustainable development. In: Tolba, M.K. (Ed.), Our Fragile World: Challenges and Opportunities for Sustainable Development. In: Vol. 2. EOLSS, Oxford, UK, pp. 1293–1310.

Onishi, A., 2002. FUGI global modeling system (FGMS200): integrated global model for sustainable development. J. Policy Model 24 (8), 561–590.

Ortiz, R.A., Markandya, A., 2009. Integrated Impact Assessment Models of Climate Change with an Emphasis on Damage Functions: A Literature Review. BC3 Working Paper Series 2009–06. Basque Centre for Climate Change, Bilbao, Spain.

Pindyck, R.S., 2013. Climate Change Policy: What Do the Models Tell Us? NBER Working Paper no. 19244. National Bureau of Economic Research, Cambridge, MA. http://www.nber.org/papers/w19244.pdf.

Pindyck, R.S., 2015. The Use and Misuse of Models for Climate Policy. NBER Working Paper no. 21097. National Bureau of Economic Research, Cambridge, MA. http://www.nber.org/papers/w21097.

Pollitt, H., Barker, A., Barton, J., Pirgmaier, E., Polzin, C., Lutter, S., et al., 2010. A Scoping Study on the Macroeconomic View of Sustainability. Final Report for the European Commission, DG Environment. Sustainable Europe Research Institute (SERI) and Cambridge Econometrics (EC), Cambridge, UK. http://ec.europa.eu/environment/enveco/studies_modelling/pdf/sustainability_macroeconomic.pdf.

Randers, J., 2012. 2052: A Global Forecast for the Next Forty Years. Chelsea Green, White River Junction, VT.

Raskin, P., Gallopín, G., Gutman, P., Al, H., Swart, R., 1998. Bending the Curve: Toward Global Sustainability. PoleStar Series Report No. 8. Stockholm Environment Institute (U.S. Center) and Tellus Institute, Boston, MA. http://www.tellus.org/pub/Bending%20the%20Curve%20-%20Toward%20Global%20Sustainability.pdf.

Raskin, P., Heaps, C., Sieber, J., Kemp-Benedict, E., 1999. PoleStar: System Manual for Version 2000. PoleStar Series Report No. 2. Stockholm Environment Institute (U.S. Center) and Tellus Institute, Boston, MA. http://www.tellus.org/pub/Polestar%20System%20Manual%20Version%202000.pdf.

Raskin, P.D., Electris, C., Rosen, R.A., 2010. The century ahead: searching for sustainability. Sustainability 2 (8), 2626–2651. https://dx.doi.org/10.3390/su2082626.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42 (January), 153–168. https://dx.doi.org/10.1016/j.gloenvcha.2016.05.009.

Richardson, J.M.,.J., 1982. A decade of global modelling. Futures 14 (2), 136–145. https://dx.doi.org/10.1016/0016-3287(82)90087-8.

Roberts, P.C., 1977. SARUM 76—a global modelling project. Futures 9 (1), 3–16.

Rojas-Romagosa, H., 2010. Modelling Human Capital Formation in WorldScan. CPB Memorandum 244. CPB Netherlands Bureau for Economic Policy Analysis, The Hague, the Netherlands. https://www.cpb.nl/sites/default/files/publicaties/download/memo244.pdf.

Rose, S.K., Diaz, D.B., Blanford, G.J., 2017. Understanding the social cost of carbon: a model diagnostic and intercomparison study. Clim. Change Econ. 8(2), unpaginated. https://dx.doi.org/10.1142/S2010007817500099.

Rosen, R.A., 2015. Critical review of making or breaking climate targets—the AMPERE study on staged scenarios for climate change. Technol. Forecast. Soc. Chang. 96 (July), 322–326. https://dx.doi.org/10.1016/j.techfore.2015.01.019.

Roson, R., van der Mensbrugghe, D., 2012. Climate change and economic growth: impacts and interactions. Int. J. Sustain. Econ. 4 (3), 270–285. https://dx.doi.org/10.1504/IJSE.2012.047933.

Rotmans, J., de Vries, B., 1997. Perspectives on Global Change: The TARGETS Approach. Cambridge University Press, Cambridge, UK.

Rotmans, J., van Asselt, M.B.A., de Bruin, A.J., den Elzen, M.G.J., de Greef, J., Hilderink, H., et al., 1994. Global Change and Sustainable Development: A Modelling Perspective for the Next Decade. GLOBO Report Series No. 4. National Institute of Public Health and Environmental Protection (RIVM), Bilthoven, the Netherlands. http://sedac.ciesin.org/mva/JR1994A/JR1994A.html.

Sano, F., Akimoto, K., Homma, T., Oda, J., Wada, K., 2012. Analysis of Asian Long-Term Climate Change Mitigation in Power Generation Sector. Research Institute of Innovative Technology for the Earth, Kyoto, Japan. http://eneken.ieej.or.jp/3rd_IAEE_Asia/pdf/paper/044p.pdf.

Sassi, O., Crassous, R., Hourcade, J.-C., Gitz, V., Waisman, H., Guivarch, C., 2010. IMACLIM-R: A modelling framework to simulate sustainable development pathways. Int. J. Global Environ. Issues 10 (1/2), 5–24. https://dx.doi.org/10.1504/IJGENVI.2010.030566.

Schneider, S.H., 1997. Integrated assessment modeling of global climate change: transparent rational tool for policy making or opaque screen hiding value-laden assumptions? Environ. Model. Assess. 2 (4), 229–249. https://dx.doi.org/10.1023/A:1019090117643.

Siegmann, H., 1987. World Modeling, Report. (originally 1985), International Institute for Comparative Social Research (Wissenschaftszentrum), Berlin, Germany. Archived by UNESCO at, http://unesdoc.unesco.org/images/0008/000890/089016eo.pdf.

Smith, C.J., Forster, P.M., Allen, M., Leach, N., Millar, R.J., Passerello, G.A., Regayre, L.A., 2018. Fair v1.3: a simple emissions-based impulse response and carbon cycle model. Geosci. Model Dev. 11 (6), 2273–2297.

Stanton, E.A., Ackerman, F., Kartha, S., 2008. Inside the Integrated Assessment Models: Four Issues in Climate Economics. SEI Working Paper WP-US-0802. Stockholm Environment Institute, U.S. Center, Somerville, MA.

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L. (Eds.), 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications. PBL Report No. 735. PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands. http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2014-integrated%20assessment%20of%20global%20environmental%20change%20with%20image30_735.pdf.

Tol, R.S.J., 2009. The economic effects of climate change. J. Econ. Perspect. 23 (2), 29–51. https://dx.doi.org/10.1257/jep.23.2.29.

United Nations Environment Programme (UNEP), 2002. Global Environment Outlook 3 (GEO-3): Past, Present and Future Perspectives. Earthscan, London, UK.

United Nations Environment Programme (UNEP), 2007. Global Environment Outlook 4 (GEO-4): Environment for Development. United Nations Environment Programme, Nairobi, Kenya.

van Asselt, M.B.A., Rotmans, J., 1995. Uncertainty in Integrated Assessment Modeling: A Cultural Perspective Based Approach. Global Dynamics and Sustainable Development Programme Report. National Institute of Public Health and the Environment (RIVM), Bilthoven, the Netherlands. http://www.rivm.nl/dsresource?objectid=beeb0e1b-efe3-4c43-a36c-848a9d1b3e1f&type=org&disposition=inline.

van der Mensbrugghe, D., 2010. The ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model, Version 7.1. World Bank, Washington, DC. http://siteresources.worldbank.org/INTPROSPECTS/Resources/334934-1314986341738/Env7_1Jan10b.pdf.

van der Mensbrugghe, D., 2011. LINKAGE Technical Reference Document, Version 7.1. World Bank, Washington, DC. http://siteresources.worldbank.org/INTPROSPECTS/Resources/334934-1314986341738/TechRef7.1_01Mar2011.pdf.

van der Mensbrugghe, D., 2013. Modeling the global economy—forward looking scenarios for agriculture. In: Dixon, P.B., Jorgensen, D.W. (Eds.), Handbook of Computable General Equilibrium Modeling. In: Vol 1B. North-Holland, Oxford, UK; Waltham, MA, pp. 933–994. https://dx.doi.org/10.1016/B978-0-444-59568-3.00014-6.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al., 2011a. The representative concentration pathways: an overview. Clim. Chang. 109 (1–2), 5–31. https://dx.doi.org/10.1007/s10584-011-0148-z.

van Vuuren, D.P., Lowe, J., Stehfest, E., Gohar, L., Hof, A.F., Hope, C., et al., 2011b. How well do integrated assessment models simulate climate change? Clim. Chang. 104 (2), 255–285. https://dx.doi.org/10.1007/s10584-009-9764-2.

van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., et al., 2014. A new scenario framework for climate change research: scenario matrix architecture. Clim. Chang. 122 (3), 373–386. https://dx.doi.org/10.1007/s10584-013-0906-1.

von Stechow, C., Minx, J.C., Riahi, K., Jewell, J., McCollum, D.L., Callaghan, M.W., et al., 2016. 2°C and SDGs: united they stand, divided they fall? Environ. Res. Lett. 11 (3), 034022. https://dx.doi.org/10.1088/1748-9326/11/3/034022.

Walsh, B.J., Rydzak, F., Palazzo, A., Kraxner, F., Herrero, M., Schenk, P.M., et al., 2015. New feed sources key to ambitious climate targets. Carbon Balance Manag. 10 (26). https://dx.doi.org/10.1186/s13021-015-0040-7 Unpaginated.

Weitzman, M.L., 2009. On modeling and interpreting the economics of catastrophic climate change. Rev. Econ. Stat. 91 (1), 1–19. https://dx.doi.org/10.1162/rest.91.1.1.

Weyant, J., 2017. Some contributions of integrated assessment models of global climate change. Rev. Environ. Econ. Policy 11 (1), 115–137. https://dx.doi.org/10.1093/reep/rew018.

Weyant, J.P., Hill, J.N., 1999. Introduction and overview. Energy J. (Special Issue on The Costs of the Kyoto Protocol: A Multi-Model Evaluation), vii–xliv. http://www.jstor.org.du.idm.oclc.org/stable/23296903.

Weyant, J., Kriegler, E., 2014. Preface and introduction to EMF 27. Clim. Chang. 123 (3–4), 345–352. https://dx.doi.org/10.1007/s10584-014-1102-7.

Weyant, J.P., de la Chesnaye, F.C., Blanford, G.J., 2006. Overview of EMF-21: multigas mitigation and climate policy. Energy J. 27 (Special Issue: Multi-Greenhouse Gas Mitigation and Climate Policy), 1–32. www.jstor.org.du.idm.oclc.org/stable/23297073.

Wigley, T.M.L., 2008. MAGICC/SCENGEN 5.3: User Manual (Version 2). National Center for Atmospheric Research, Boulder, CO. http://www.cgd.ucar.edu/cas/wigley/magicc/UserMan5.3.v2.pdf.

Wigley, T.M.L., Raper, S.C.B., 2001. Interpretation of high projections for global-mean warming. Science 293 (5529), 451–454. https://dx.doi.org/10.1126/science.1061604.

4

Introducing International Futures

It would be unwarranted to suggest that International Futures (IFs) is some culmination of the evolutionary process described in Chapter 3, or even that its continued development will address most of the challenges as we look ahead in global modeling. Still, IFs is a very strong contemporary system drawing on the traditions of both world modeling and integrated assessment modeling. For that reason, and because of this author's long development of it, the rest of the volume will elaborate the elements of IFs in extensive presentation of, and comparison with, other models. This chapter provides foundational information about IFs.

4.1 STRUCTURAL OVERVIEW OF IFs

The International Futures project, with early roots in world modeling and subsequent evolutionary development as an integrated assessment model, has always recognized the close interaction of human, social, and sustainable development. IFs is a large-scale, long-term, integrated, dynamically recursive global modeling system with 1-year time steps through 2100.[1] Its broad purpose is to serve as a thinking tool for the analysis of near- through

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[1] The IFs team has grown over the years under the leadership of Barry Hughes, the founder of the IFs system and founding director of the Pardee Center for International Futures, and Jonathan Moyer, the current director of the Center. Many members have contributed very substantially to its development and therefore to the work reported here. Mohammod Irfan developed the education model. Randall Kuhn, Cecilia Peterson, and José Solórzano were critical in the development of the health model. Dale Rothman and Mohammod Irfan took the lead with respect to infrastructure, with critical input from Eli Margolese-Malin and Jonathan Moyer. Devin Joshi, Tim Sisk, José Solórzano, and Jonathan Moyer supported the creation of the governance model. Steve Hedden has developed a water submodule for the environment model, and Dale Rothman has updated and elaborated the representation of global warming and its impacts back to agriculture and health, as well as revising the agricultural model. José Solórzano, with input also from Mohammod Irfan, has led the elaboration of the user interface, and with support from Jaime Meléndez created the web-based version of the IFs system. Janet Dickson has been editor-in-chief across the *Patterns of Potential Human Progress* series plus author of one of them and many other writings. Jonathan Moyer's

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long-term country-specific, regional, and global futures across multiple issue areas. IFs represents 186 countries and their interactions. It incorporates a database of more than 4200 historical series across its issue areas. The system is freely available for others to use in downloadable and web-based versions (www.Pardee.du.edu), and the model code itself is under public license. These characteristics have made the IFs system widely used as an aide to thought, analysis, and action related to global futures.

Fig. 4.1 identifies the hard-linked models within IFs. The extensive linkages across the models include forward and backward connections across the human (green), social (blue), and sustainable (black) development components. This chapter will provide brief model summaries. Subsequent chapters will considerably elaborate their structure and interconnections but still be unable to provide full documentation of them. The reader interested in full

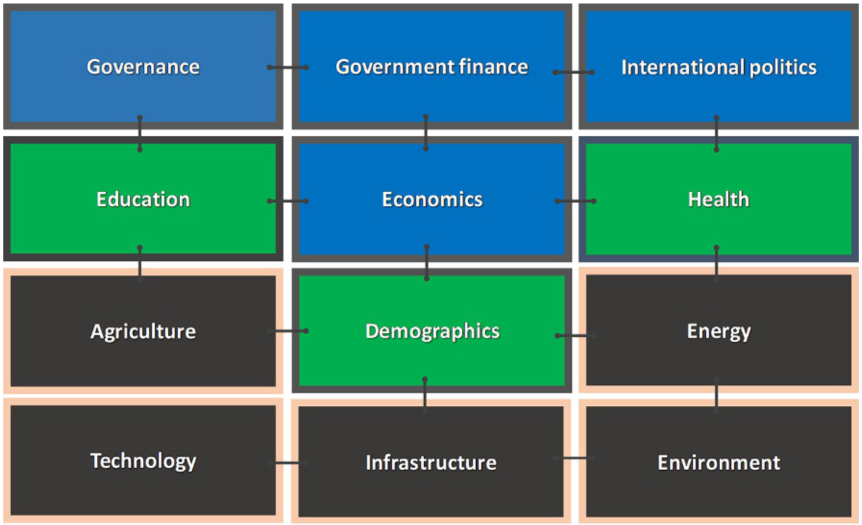

FIG. 4.1 **The models in the International Futures system.**
Note: Green indicates models in IFs primarily focused on human development, blue represents socioeconomic development, and black shows models especially important to sustainable development. Source: IFs project.

presentations of IFs and trainings in its use (also those by David Bohl, Steve Hedden, and others) have provided invaluable feedback to model and interface enhancement. Other full-time team members with a broad range of writing, research, and training responsibilities now or in the past include Drew Bowlsby, Althea Ditter, Zachary Donnenfeld, Lisa Lane Filholm, Alanna Markle, John McPhee, Kanishka Narayan, Alex Porter, Jessica Rettig, Andrew Scott, and Sara Turner. Mickey Rafa is the overall project manager, also taking over financial responsibilities from Janet Dickson. The set of research assistants and other team members over time is far too large to list, but has supported a wide variety of project activities, including the creation and maintenance of the huge database, the researching and often writing of support papers, and maintenance of the website. Dramatically far from least in our list of acknowledged contributors, Frederick S. Pardee has been generous at multiple times and in many ways in his support of the creation of the Frederick S. Pardee Center for International Futures and the continued development and use of the International Futures system.

detail on structures and equations should go the Pardee Center/IFs website at www.Pardee.du.edu. Technical documentation on each model is available there in working papers (http://pardee.du.edu/working-papers) and in a wiki (http://pardee.du.edu/wiki/Main_Page). Still other documentation at that site provides general training and special help with the extensive interface and with scenario analysis.

A quick introduction to each model can be useful. Subsequent chapters will clarify specialized and perhaps unfamiliar terminology (the summary here cannot completely avoid its use):

- The *demographic model* uses standard cohort-component representation, portraying demographics in 5-year categories (adequate for most uses), but building on underlying 1-year categories to be consistent with its computational time steps. Unlike most demographic forecasting systems, it computes both fertility and mortality endogenously (migration is specified exogenously). The availability in the IFs system of both education and health models greatly facilitates such endogenous treatment. Data come every 2 years from the United Nations Population Division's latest revision updates.
- The six-sector *economic model* structure is general equilibrium seeking, in which a Cobb-Douglas formulation drives production and in which multifactor productivity is substantially an endogenous function of human capital, social capital/governance, physical capital, and knowledge capital. Although capital and labor accumulations are very important, in long-term forecasting the formulations around productivity heavily shape dynamics within the economic model and its interaction with other models. There is also a foundational representation of global technology development and diffusion that facilitates further representation of productivity dynamics and intercountry convergence or lack thereof. A linear expenditure system determines household demand. A social accounting matrix structures flows across sectors and agent categories, assuring full financial flow consistency. The model includes representation of financial markets (savings and investment), labor markets, and the informal economy. Data come heavily from the World Bank and the Global Trade Analysis Project.
- The *education model* represents the progression of students, year by year, through primary, lower secondary, upper secondary, and tertiary education, with some representation also of vocational education and the portion of tertiary students in science and engineering. Key dynamic elements include entry (or transition) rates to the various levels and the persistence or survival of students year by year. Government spending on education, both per student and overall, is also an important component. Representation of quality augments quantity of education, and adult populations carry quantity and quality history with them as they age. The UNESCO Institute of Statistics is the source of most progression data, while Barro and Lee (2013, 2015) and Lee and Lee (2016) provide adult attainment data.
- The IFs *health model* is a hybrid and integrated approach to forecasting health outcomes. It is hybrid because it uses drivers at both distal (i.e., income, education, and technology) and proximate (e.g., risk factors such as smoking rates and undernutrition) levels to produce outcomes, and integrated because both drivers and outcomes are situated within the greater IFs system, allowing for the incorporation of forward linkages and feedback loops.

This approach enables users to explore dynamic age, sex, and country-specific health outcomes related to 15 individual and clustered causes of mortality and morbidity through 2100. Data come from the Global Burden of Disease project.

- The *energy and agricultural models* are partial equilibrium with a physical basis that is translated to monetary terms for interface with the economic model. The energy model represents reserves and resources on the production side, which differentiates oil, gas, coal, hydroelectric, nuclear, and other renewable sources. The dynamics around the stocks of fossil resources and their use and those around development of renewable forms are critical for forward linkages to the environment. The agricultural model represents land usage on the production side, which differentiates crops, meat, and fish. Default representation of trade in the energy, agricultural, and broader economic models uses a pool approach rather than bilateral flows, but a bilateral option exists.
  - On the demand side, the *energy model* is driven by the size of economies and populations, along with energy intensities of human activity. On the supply side, production requires not only resource bases but also the accumulation of capital stock via investment in competition with other sectors. Trade responds to differential cost and price structures across countries. Interventions by the user can represent geopolitically based constraint in the growth of production and decisions to restrain exports. Global prices clear the market over time (although inventories rise and fall, generating price signals), but user interventions can override market prices. Most data are from the International Energy Agency. Other data sources support representation of unconventional fossil resources (shale oil and gas, tight oil, coal-bed methane, etc.).
  - Demand in the *agricultural model* responds to population and income levels; assumptions about future meat demand of emerging countries are important to long-term dynamics. On the supply side, crop yield per hectare is critical. Trade and price equilibration are similar to those in energy. Most data come from the Food and Agriculture Organisation of the United Nations.
- The *infrastructure model* addresses selected forms for transportation (roads and paved percentage of them), electricity generation and access, water and sanitation, and information and communications technology (landlines, mobile telephones, and broadband connectivity by mobile phone or line). Demand and supply are related through the interaction of financial requirements and availability of private and public funds. Many parameters for setting and pursuing targets of access are available, and data come from many sources.
- The *environmental model* links closely to energy and agriculture because both demands from those systems (for fossil fuels, land, fish, and water) and outputs from them (especially carbon dioxide) drive the environmental model. The model represents atmospheric carbon emissions and feeds accumulated stocks forward to temperature and precipitation changes that, in turn, affect agriculture. It also represents water supply and demand.
- *Technology* is not a separate model in the IFs system. Instead, technology is represented across and within all the other models—for instance, in changing capital cost structures for energy forms and in rates of progress in raising agricultural yields.
- The *domestic governance model* includes three dimensions of governance—security, capacity, and inclusion—each of which has two elaborating subdimensions. Variables

connected to the subdimensions include risk of domestic conflict, corruption, democracy, and gender empowerment. Variables across the other models, especially income and education levels, drive change in governance. Change in the three governance dimensions, in turn, drives significant aspects of the integrated system, including economic productivity.

- Revenues and expenditures are the fundamental elements of the *government finance model*. Revenues involve streams from firms, households, and, for some countries, foreign aid from other governments. Expenditures involve transfer payments and direct expenditure on the military and on education, health, infrastructure, R&D, and a residual "other" category. Government revenues and expenditures are fully integrated within the larger social accounting matrix system.
- The *international political model* calculates national material power from inputs such as economic output, population, military spending, and a proxy for technological advance, but also allows the user flexibility with respect to including and weighting these and other elements. Whether countries pose a threat to each other is a complex function of such power and of a number of other variables, including level of democratization and trade relationships. The variables of the international political model are primarily satellites to the rest of the IFs system, but power dynamics do affect military spending levels directly, and therefore all government finance indirectly. The IFs team has an ongoing major data-making project to enhance existing series on international relationships and to build new ones, including those representing diplomatic interconnections (therefore soft power) and even global structures.

As a hybrid system, IFs does not fall neatly into econometric, systems dynamics, or any other single model category. It is a structure-based, agent-class driven, dynamic modeling system. Households, governments, and firms are major agent classes. The system draws upon standard approaches to modeling specific issue areas whenever possible, extending those as useful and integrating them across issue areas. One important reason for a hybrid approach is that it allows the combination of close attention to stocks and flows (and differentiation among them, as in systems dynamics) and to data and estimation of relationships. IFs further combines these traditions with a heavy use of algorithmic or rule-based elements and even, when it comes to equilibration, with some elements of control theory. Maintenance of accounting structures is very important in the overall system, including the use of them to track aging populations (cohort component structure), financial flows among agent classes (social accounting), energy resources and production/demand, land use, and carbon stocks and flows.

In terms of computer languages, the project began with Fortran and moved to Microsoft Visual Basic with supplemental objects. It should complete migration to VB-Net in 2019.

The strengths of the IFs system of models include (1) the integration of a wide range of structures across global issue systems as well as of the agent-driven flows that alter those structures over time, (2) the extensive data foundations of the system, and (3) its usability and transparency. Weaknesses include those common to most such models, including substantial uncertainties around (1) some important data (such as ultimately recoverable energy resources), (2) some important relationships (including drivers of economic productivity), and (3) some fundamentally important key dynamic forces (such as technological advance).

Another potential weakness of the system is its complexity, which is the potentially negative side of integrating many models. The project has attempted to ameliorate the challenges of that complexity not only via its documentation, but also via its user interface (for a user's guide, see Turner et al., 2015).

4.2 THE USER INTERFACE OF IFs

The IFs interface has three basic functionalities: (1) data analysis, (2) exploring model runs (including the Base Case), and (3) developing and running new scenarios. Many users begin with considerable exploration of the model's base case before turning to scenarios. Our discussion here begins with data analysis because it is where members of the project team begin. Then we turn to exploration of pre-existing scenarios and to building new ones.

4.2.1 Data Analysis

The IFs database contains more than 4200 series, covering as many as possible (depending on data availability within individual series) of the 186 countries in the model and the years from 1960 through most recent data (for some series, data go back as far as 1800). It draws widely from standard sources such as the United Nations (including demographic data), the World Bank (considerable economic and social data), the International Monetary Fund (international financial data), the Organisation for Economic Co-operation and Development (social expenditures), and the Global Trade and Analysis Project (input-output matrices and income returns to skilled and unskilled households). The associated IFs data dictionary, documenting each series, additionally credits a large number of specialized sources (see Hughes et al., 2012a).

IFs incorporates a variety of tools for extensive data analysis. The tools include cross-sectional (bivariate and multivariate) and longitudinal statistical analysis, with graphical display as well as statistical computation. They also include a GIS mapping capability for simple univariate display.

The existence of the large database within IFs allows display of our Base Case and other scenarios in the context of past patterns, and large numbers of the IFs variables have historical analogues that the interface can show with the forecast. One significant advantage of this is that it makes transients (jumps from historical values or sharp pattern bends) very obvious.

The project also undertakes regular comparison of its forecasts with those from other projects and analysis of the bases for differences. In fact, the system increasingly builds the forecasts/projections of others into its "database" to facilitate immediate comparison. For instance, the IFs database includes sets of alternative projections generated in the Shared Socioeconomic Pathways initiative (see Section 3.3.2.1).

One challenge created by having such a large database is the regular updating of it. Chapter 2 discussed this as a general problem for world modeling and described some of the tools that the IFs interface includes to facilitate updating the database, such as a concordance table for mapping country names across all major data sources and the use of a semi-automated process for pulling multiple data series from key sources (see Box 2.1).

Another challenge, faced by all large-scale global modeling efforts, is initialization of variables and parameters. Updating the base year of large-scale models often involves several person-years of effort. Basic problems include missing data, incompatible data from different data sources, and simple unit conversion. To simplify initialization and to allow flexible re-regionalization of the model, IFs relies on a preprocessor that uses a staged sequence of data-processing steps to create a new initialization (see again Box 2.1). The preprocessor, in turn, draws upon the modeling platform's statistical analysis capability for estimating missing values.

4.2.2 Display of Results

The display capabilities of the IFs platform contain most standard formats, such as tables, line graphs, bar charts, pie diagrams, scattergrams, and maps. The IFs system offers users the ability to choose any variables or parameters in the model and to display those over time in any combination and with any output format. In addition, computational capabilities exist to combine and/or transform existing variables into ones newly defined by the user.

The wealth of variables and parameters in the model make it difficult, however, for beginning users to identify important focal points. Therefore, the IFs interface has multiple levels of display that serve different users and/or different needs. These include a Flexible Display menu option for easy access to model forecast results (Base Case or other scenarios), with natural language descriptions of variables or grouped sets of them.

In addition, there are many specialized display capabilities. One shows population variables using the typical age-sex format. Similar displays show education by level across age and sex cohorts or cohort-based variables from the World Values Survey. Another facilitates analysis of progress toward the Sustainable Development Goals (SDGs). Others show social accounting matrices, Lorenz curves with calculation of associated Gini indices for any variable in the model, or Country Profiles and Basic Reports for any country or country grouping (including the standard but differing groupings from a large number of international organizations and research projects). Further, there is also a Self-Managed Display option that calls up a listing of all variables and parameters in the model (with both computer code-based names and extended definitions), allowing the user to mix and match selections.

4.2.3 Creation of Scenarios

The third major functionality of the interface facilitates the creation of new scenarios. A scenario form embedded in the IFs interface allows changes to all initial conditions and parameters of the model and allows variations of parameter values over time. It supports the saving of narrowly based parameter changes (often used to assess the sensitivity of the system to policy-linked interventions, and perhaps more appropriately referred to as "cases" rather than scenarios), and also the accretion of multiple changes into true scenarios with new and coherent stories of the future. The model is available with a large library of such intervention files to produce and explore scenarios like those that Chapter 9 discusses.

With respect to major transformations, the IFs project has used the system's capabilities to build sets of scenarios around dramatic advances in life expectancy, and the project has also mapped approaches to representing the possible impacts of major advances in artificial intelligence. Yet, even more traditional scenarios, when large numbers of interventions are mutually reinforcing and compounding, can become significantly transformative. For instance, the IFs project has built representations of the Shared Socioeconomic Pathways discussed in Chapter 3. IFs contains multiple other sets of scenarios, including four with roots in the work of the Global Scenario Group (GSG) that focused on alternative positive and negative transformative paths. Variations of the GSG scenarios have been used in the Global Environment Outlook work of the United Nations Environment Programme and other projects (see Chapter 9). IFs is also distributed with quantifications of scenarios from the Global Trends reports of the US National Intelligence Council. In addition, a large number of scenarios (some more narrowly policy-focused and others more transformative) were developed and elaborated in IFs in support of the *Patterns of Potential Human Progress* series that emanated from the Pardee Center for International Futures. These scenarios were directed at reducing poverty, advancing education, improving health, building infrastructure, and transforming governance globally.

In the standalone version of IFs, scenario parameter files are available that allow the running and recreation of results from the projects already mentioned and nearly all of those discussed in the next section. In the web-based version of IFs, not only are the scenario parameter files available but most of the scenarios are prerun and ready for analysis and use by others.

4.3 USERS AND USES OF IFs

IFs has supported a wide range of scientific analyses and policy-oriented projects. An earlier overview of such analyses and projects appears in Hughes (2016); see also Hughes (1999) and Hughes and Hillebrand (2006). Major projects are listed in the following paragraphs by type of sponsoring organization.

Project applications in association with intergovernmental organizations. IFs was a core component of two projects exploring the New Economy sponsored by the European Commission (Hughes and Johnston, 2005; Moyer and Hughes, 2012). In the Western hemisphere, the Pardee Center collaborated with the Atlantic Council on a project on regional futures with the Inter-American Development Bank (Marczak et al., 2016). In other regional work, the Pardee Center produced a report for the New Partnership for Africa's Development (NEPAD), the planning and coordinating technical body of the African Union, on the prospects for eradicating hunger in Africa by 2025 (Hedden et al., 2016). The Center continues collaboration with NEPAD, recently renamed the African Union Development Agency (AUDA), in its Agenda 2063 project, exploring patterns and potential for development across the continent.

Globally, IFs provided forecasts for the fourth Global Environment Outlook (GEO) of the United Nations Environment Programme (UNEP, 2007) as well as supported the sixth GEO (Moyer and Bohl, 2019; Moyer and Hedden, 2018). Also on the environmental side, the IFs project and personnel have connected with the Shared Socioeconomic Pathways (SSP) initiative (O'Neill et al., 2017) that, in turn, links to the work of the Intergovernmental Panel on

Climate Change. IFs project work should be able to strengthen the internal coherence of the five SSP scenarios, given that issue-specific forecasts for them have come from different modeling groups with largely unconnected models; IFs also can help extend the issue reach of the SSPs across the Sustainable Development Goals (SDGs).

IFs was used in analysis of two United Nations Development Programme Reports around issues of sustainability, equity, and human progress (UNDP, 2011, 2013; see Hughes, 2013, and Hughes et al., 2011a, 2012b for supporting research). In addition, the Pardee Center has teamed with the UNDP's Bureau for Policy and Programme Support in collaboration with New York-based and regional UNDP personnel in support of many country-based SDG initiatives.

In more specific issue areas, the United States Institute of Peace commissioned a study with IFs and other projects on fragile or vulnerable states (Hughes et al., 2011c), and the World Bank supported a study of the prospects for eradicating poverty in fragile and conflict-afflicted states (Burt et al., 2014; Milante et al., 2016). Further, for the report of the International Commission on Financing Global Education Opportunity (2016) the Pardee Center produced a background study (Dickson et al., 2016) with special attention to the goal of universal upper-secondary education.

Project applications focusing on national and subnational analysis. Forecasts from IFs heavily supported the Global Trends 2020, 2025, and 2030 reports to the president by the US National Intelligence Council (NIC, 2004, 2008, 2012). The Pardee Center also has provided background information to the NIC on the advance and impacts of artificial intelligence (AI); Scott et al. (2017) document our work on the topic including adding early treatment of AI to IFs. The Center has also supported US intelligence and the army in extensive database development projects. In addition, IFs supported a study of the future of education in the southern Africa region (Irfan and Margolese-Malin, 2012), and the Pardee Center has worked with the government of the Western Cape province of South Africa on a series of policy papers and on embedding use of the IFs system in the government's policy-making processes. The Center similarly collaborated on several studies with the National Center for Strategic Planning (Centro Nacional de Planeamiento Estratégico or CEPLAN) in the government of Peru (see CEPLAN (2015a) for its own description of the IFs system and see CEPLAN (2015b) and CEPLAN (2016) for its work with IFs on the future of education in Peru and on Peru's informal economy). Bohl et al. (2015) documented the extension and use of IFs in the study of the informal economy. Similarly, the Pardee Center has provided reports to the US Agency for International Development to inform its Country Development Cooperation Strategy 2017–21 and broader activities, notably for Uganda (Moyer et al., 2015), South Africa (the country) (Bohl et al., 2017b), the countries of Southern Africa as a region (Bohl et al., 2017a), and the countries of Central America.

Project applications with international nongovernmental organizations The Overseas Development Institute used IFs forecasts and scenarios on global poverty in two major reports (Shepherd et al., 2013, 2014) as well as in other work, including a project for Save the Children.[2] In partnership with the Institute for Security Studies (ISS), a pan-African think tank headquartered in South Africa, the project has produced a series of policy-oriented papers on African issues (available at http://pardee.du.edu/policy-briefs and on the ISS website).

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[2] Private correspondence with Amanda Lenhardt, a senior research and policy advisor at Save the Children.

These cover topics ranging from the future of water and sanitation (Eshbaugh et al., 2011) through attaining food security (Moyer and Firnhaber, 2012) to gas fracking in South Africa (Hedden et al., 2013) and fighting communicable diseases, including AIDS and malaria (Narayan and Donnenfeld, 2016). IFs serves as the primary analytic tool for the African Futures and Innovation Programme based at the ISS (Cilliers et al., 2011), including its support of the South African government in a variety of projects. The Pardee Center supported the SENS research foundation in analysis of the broader impacts of much extended life expectancies (Hughes et al., 2014b, 2015), Population Services International on a study of the health impact of moving from solid-fuel to modern cookstoves in households (Kuhn et al., 2016), and Water for People in exploring the impact of providing safe water and sanitation. Further, we collaborated with Action Against Hunger in a study of the ability to eliminate and/or treat severe acute malnutrition.

Corporate and think tank applications. A smaller stream of work has supported corporate and think tank research projects. In association with the Atlantic Council, the Pardee Center used IFs in projects sponsored by Zurich Insurance Group on the economic risks and opportunities associated with cyber security (Zurich Insurance Group, 2015) and with demographic change, primarily aging (Bohl et al., 2016; Burrows, 2016). It also supported PricewaterhouseCoopers (PwC) in a study of the future of the Pacific Alliance (PwC, 2016) and Lockheed Martin in a project on the changing global security environment.

Published third-party research and analysis. The Center has not kept track of the numbers of students, scholars, policy analysts, and others who have, over the years, used or at least perused the IFs system, but there is little question that many thousands have. Some of that use has led to published third-party research and analysis that relied heavily on the system. See, for example, Birkmann et al., 2013; Cantore, 2011, 2012; Cantore and Cali, 2015; Casetti, 2003; Cave et al., 2009; Chadwick, 2006a, 2006b; Cilliers and Schúnemann, 2013; Cilliers and Sisk, 2013; Hillebrand, 2008, 2010; Hillebrand and Closson, 2015; McCauley, 2014; Pearson, 2011; and West et al., 2013.

The most substantial use of the International Futures (IFs) system in recent years was the publication by the Pardee Center of a five-volume flagship series, *Patterns of Potential Human Progress*, on the global issues of poverty, education, health, infrastructure, and governance. Paradigm Publishers in Boulder, Colorado, and Oxford University Press in New Delhi, India, copublished the volumes (in chronological sequence, the citations are Hughes et al., 2009; Dickson et al., 2010; Hughes et al., 2011b; Rothman et al., 2014; Hughes et al., 2014a). The production of this series served three major purposes: (1) motivating the development of entirely new models within the forecasting system, several of them—like health, infrastructure, and governance—fundamentally unique, (2) generating substantial exposure of the system to other users for their own analyses, and (3) using the IFs system as a tool to explore the global pursuit of the poverty reduction goal of the Millennium Development Goals (Hughes and Irfan, 2008) and, more recently, of the poverty eradication goal of the Sustainable Development Goals.

4.4 LOOKING AHEAD

The following four chapters continue to provide information on the structure of IFs, looking at its models as organized in Fig. 4.1 and therefore roughly grouped by human, social, and sustainable development. In reality, of course, none of the models fits solely into a single broad category. While the focus in Chapter 5 on human development will begin by looking at demographics, and that in Chapter 6 on social development will begin with economics, no one would argue that those two models and issue areas are not tightly related to each other and to the prospects for sustainable development.

Across the chapters, treatment of each issue area will lay some initial groundwork with respect to key concepts, systemic structures, data, and transitions, survey briefly the similarities and differences in modeling approaches across a range of existing models, identify some of the key formulations and substructures of such models, provide more detail on the treatment in IFs, and at least briefly compare IFs core scenario projections with those of others.

References

Barro, R.J., Lee, J.-W., 2013. A new data set of educational attainment in the world, 1950–2010. J. Dev. Econ. 104 (September), 184–198. https://dx.doi.org/10.1016/j.jdeveco.2012.10.001.

Barro, R.J., Lee, J.-W., 2015. Education Matters: Global Schooling Gains from the 19th to the 21st Century. Oxford University Press, New York, NY.

Birkmann, J., Cutter, S.L., Rothman, D.S., Welle, T., Garschagen, M., van Ruijven, B., et al., 2013. Scenarios for vulnerability: opportunities and constraints in the context of climate change and disaster risk. Clim. Chang. 133 (1), 53–68. https://dx.doi.org/10.1007/s10584-013-0913-2.

Bohl, D., Hughes, B.B., Irfan, M.T., Margolese-Malin, E.S., Solórzano, J., 2015. The Informal Economy in the IFs Model. Report for Peru's Centro Nacional de Planeamiento Estratégico (CEPLAN). Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/Bohl_2015_Ceplan.pdf.

Bohl, D.K., Hughes, B.B., Johnson, S., 2016. Understanding and Forecasting Demographic Risk and Benefits. Report for Zurich Insurance Group in collaboration with the Atlantic Council. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://pardee.du.edu/sites/default/files/Demographic%20Risk%20Report%20v44%20%28Final%29.pdf.

Bohl, D.K., Hedden, S., Moyer, J.D., Narayan, K., Rettig, J., 2017a. Development Trends Report for Southern Africa. Research Paper prepared for United States Agency for International Development. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://pardee.du.edu/sites/default/files/USAIDSouthernAfricaDevelopmentTrends.pdf.

Bohl, D.K., Hedden, S., Moyer, J.D., Narayan, K., Scott, A.C., 2017b. Development Trends Report for South Africa. Research Paper prepared for United States Agency for International Development. Pardee Center for International Futures, University of Denver, Denver, CO. http://pardee.du.edu/sites/default/files/USAIDDevelopmentTrendsSouthAfricaApril2017.pdf.

Burrows, M.J., 2016. Reducing the Risks from Rapid Demographic Change. Report of the Atlantic Council in association with the Pardee Center for International Futures and the Zurich Insurance Group. The Atlantic Council, Washington, DC. http://www.atlanticcouncil.org/images/publications/Reducing_the_Risks_from_Rapid_Demographic_Change_web_0909.pdf.

Burt, A., Hughes, B.B., Milante, G., 2014. Eradicating Poverty in Fragile States: Prospects of Reaching the 'High-Hanging' Fruit by 2030. WB Policy Research Working Paper no. 7002. World Bank, Washington, DC. http://documents.worldbank.org/curated/en/2014/08/20040315/eradicating-poverty-fragile-states-prospects-reaching-high-hanging-fruit-2030.

Cantore, N., 2011. Future Paths of Poverty: A Scenario Analysis with Integrated Assessment Models. CPRP Working Paper 200. Overseas Development Institute, London, UK. https://assets.publishing.service.gov.uk/media/57a08ad6e5274a31e00007de/WP200-Cantore.pdf.

Cantore, N., 2012. Sustainability of the energy sector in the Mediterranean region. Energy 48 (1), 423–430. https://dx.doi.org/10.1016/j.energy.2012.06.019.

Cantore, N., Cali, M., 2015. The impact of temporary migration on source countries: a simulation exercise. Int. Migr. Rev. 49 (3), 697–726. https://dx.doi.org/10.1111/imre.12178.

Casetti, E., 2003. Power shifts and economic development: when will China overtake the USA? J. Peace Res. 40 (3), 661–675. https://dx.doi.org/10.1177/00223433030406003.

Cave, J., van Oranje-Nassau, C., Schindler, H.R., Shehabi, A.'a., Brutscher, P.-B., Robinson, N., 2009. Trends in Connectivity Technologies and their Socioeconomic Impacts. Final Report of the Policy Options for the Ubiquitous Internet Society. RAND Europe, Cambridge, UK; Brussels, Belgium. http://www.rand.org/content/dam/rand/pubs/technical_reports/2009/RAND_TR776.pdf.

Centro Nacional de Planeamiento Estratégico (CEPLAN), 2015a. Modelo International Futures: Fundamentos, Adaptación y Uso para el Planeamiento Estratégico del Perú. Serie: Documento Metodológico no. 3. Centro Nacional de Planeamiento Estratégico, San Isidro, Lima, Perú (update). http://www.ceplan.gob.pe/content/modelo-international-futures-ifs-fundamentos.

Centro Nacional de Planeamiento Estratégico (CEPLAN), 2015b. Pronósticos y Escenarios: Educatión en el Perú al 2030—La Aplicación del Modelo International Futures. Serie: Avance de Investigación no. 7. Centro Nacional de Planeamiento Estratégico, San Isidro, Lima, Perú. http://www.ceplan.gob.pe/documentos_/pronosticos-y-escenarios-educacion-en-el-peru-al-2030-la-aplicacion-del-modelo-international-futures/.

Centro Nacional de Planeamiento Estratégico (CEPLAN), 2016. Economía Informal en Perú: Situación Actual y Perspectivas. Serie: Avance de Investigación no. 8. Centro Nacional de Planeamiento Estratégico, San Isidro, Lima, Perú. http://www.ceplan.gob.pe/documentos_/economia-informal-en-peru/.

Chadwick, R.W., 2006a. Korea 2020, national security futures, development, democracy, and choices: building a Korea peace structure. J. Peace Stud. 7 (2), 7–35 (Korean Association of Peace Studies).

Chadwick, R.W., 2006b. Levels of Meaning and Levels of Analysis: Exploring Micro-Macro, Local-Global Interface Problems with the International Futures Simulation (IFs), Using Hawaii as an Exemplar. Paper presented at the International Studies Association Conference at Bilgi University, Istanbul, August 24–27.

Cilliers, J., Schúnemann, J., 2013. The Future of Intrastate Conflict in Africa: More Violence or Greater Peace? ISS Paper no. 246. Institute for Security Studies, Pretoria, South Africa. https://issafrica.s3.amazonaws.com/site/uploads/Paper246.pdf.

Cilliers, J., Sisk, T.D., 2013. Assessing Long-Term State Fragility in Africa: Prospects for 26 'More Fragile' Countries. ISS Monograph Number 188. Institute for Security Studies, Pretoria, South Africa. https://issafrica.s3.amazonaws.com/site/uploads/Mono188.pdf.

Cilliers, J., Hughes, B., Moyer, J., 2011. African Futures 2050: The Next 40 Years. Monograph 175. Institute for Security Studies and Frederick S. Pardee Center for International Futures, Pretoria, South Africa; Denver, CO. https://issafrica.s3.amazonaws.com/site/uploads/Mono175.pdf.

Dickson, J.R., Hughes, B.B., Irfan, M.T., 2010. Advancing Global Education. Vol. 2 of the Patterns of Potential Human Progress Series. Paradigm Publishers and Oxford University Press, Boulder, CO; New Delhi, India.

Dickson, J.R., Irfan, M.T., Hughes, B.B., 2016. USE 2030: Exploring Impacts, Costs, and Financing. Background Paper provided by the Frederick S. Pardee Center for International Futures for the International Commission on Financing Global Education Opportunity. International Commission on Financing Global Education Opportunity, New York, NY. http://report.educationcommission.org/wp-content/uploads/2016/11/USE-2030-Exploring-Impacts-Costs-and-Financing.pdf.

Eshbaugh, M., Firnhaber, E., McLennan, P., Moyer, J.D., Torkelson, E., 2011. Taps and Toilets: How Greater Access Can Radically Improve Africa's Future. African Futures Brief no. 1. Institute for Security Studies and Frederick S. Pardee Center for International Futures, Pretoria, South Africa; Denver, CO. http://www.pardee.du.edu/taps-and-toilets-how-greater-access-can-radically-improve-africa%E2%80%99s-future.

Hedden, S., Moyer, J.D., Rettig, J., 2013 (December). Fracking for Shale Gas in South Africa: Blessing or Curse? African Futures Paper no. 9. Institute for Security Studies and Frederick S. Pardee Center for International Futures, Pretoria, South Africa; Denver, CO. http://pardee.du.edu/sites/default/files/PolicyBrief_AFP_FrackingSA.pdf.

Hedden, S., Hughes, B.B., Rothman, D.S., Markle, A.J., Maweni, J., Mayaki, I.A., 2016. The Elimination of Hunger and Food Insecurity on the African Continent by 2025: Conditions for Success. The New Partnership for African Development Planning and Coordinating Agency (NEPAD) and the Frederick S. Pardee Center for International Futures, Midrand, South Africa; Denver, CO. http://www.nepad.org/resource/ending-hunger-africa-elimination-hunger-and-food-insecurity-african-2025-conditions-success.

Hillebrand, E.E., 2008. The global distribution of income in 2050. World Dev. 36 (5), 727–740. https://dx.doi.org/10.1016/j.worlddev.2007.05.013.

Hillebrand, E.E., 2010. Deglobalization scenarios: who wins? who loses? Glob. Econ. J. 10 (2), 1–19. https://dx.doi.org/10.2202/1524-5861.

Hillebrand, E.E., Closson, S., 2015. Energy, Economic Growth, and Geopolitical Futures. MIT Press, Cambridge, MA.

Hughes, B.B., 1999. The International Futures (IFs) modeling project. Simul. Games 30 (3), 304–326. https://dx.doi.org/10.1177/104687819903000306.

Hughes, B.B. (Ed.), 2013. Development-Oriented Policies and Alternative Human Development Paths: Aggressive but Reasonable Interventions. Prepared by the Frederick S. Pardee Center for International Futures. UNDP Occasional Paper 2013/05. Human Development Report Office, United Nations Development Programme, New York, NY. http://hdr.undp.org/sites/default/files/hdro_1305_pardee.pdf.

Hughes, B.B., 2016. International Futures (IFs) and integrated, long-term forecasting of global transformations. Futures 81 (August), 98–118. https://dx.doi.org/10.1016/j.futures.2015.07.007.

Hughes, B.B., Hillebrand, E.E., 2006. Exploring and Shaping International Futures. Paradigm, Boulder, CO.

Hughes, B.B., Irfan, M.T., 2008. Assessing strategies for reducing global poverty. In: Reuveny, R., Thompson, W.R. (Eds.), North and South in the World Political Economy. Blackwell, Malden, MA; Oxford, UK, pp. 313–340.

Hughes, B.B., Johnston, P.D., 2005. Sustainable futures: policies for global development. Futures 37 (8), 813–831. https://dx.doi.org/10.1016/j.futures.2005.01.017.

Hughes, B.B., Irfan, M.T., Khan, H., Kumar, K.B., Rothman, D.S., Solórzano, J.R., 2009. Reducing Global Poverty. Vol. 1 of the Patterns of Potential Human Progress Series. Paradigm Publishers and Oxford University Press, Boulder, CO; New Delhi, India.

Hughes, B.B., Irfan, M.T., Moyer, J.D., Rothman, D.S., Solórzano, J.R., 2011a. Forecasting the Impacts of Environmental Constraints on Human Development. Human Development Research Paper 2011/08. United Nations Development Programme, New York, NY. http://hdr.undp.org/sites/default/files/hdrp_2011_08.pdf.

Hughes, B.B., Kuhn, R., Peterson, C.M., Rothman, D.S., Solórzano, J.R., 2011b. Improving Global Health. Vol. 3 of the Patterns of Potential Human Progress Series. Paradigm Publishers and Oxford University Press, Boulder, CO; New Delhi, India.

Hughes, B.B., Moyer, J.D., Sisk, T.D., 2011c. Vulnerability to Interstate Conflict: Evaluating Quantitative Measures. Peaceworks Report no. 72. United States Institute of Peace, Washington, DC. http://www.usip.org/sites/default/files/Vulnerability_to_Intrastate_Conflict.pdf.

Hughes, B.B., Chesebro, J., Hossain, A., 2012a. The Database of International Futures (IFs). Working Paper 2012.12.16. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/2012.12.16_IFsDocumentation_Database_v2.pdf.

Hughes, B.B., Irfan, M.T., Moyer, J.D., Rothman, D.S., Solórzano, J.R., 2012b. Exploring future impacts of environmental constraints on human development. Sustainability 4 (5), 958–994. https://dx.doi.org/10.3390/su4050958.

Hughes, B.B., Joshi, D.K., Moyer, J.D., Sisk, T.D., Solórzano, J.R., 2014a. Strengthening Governance Globally. Vol. 5 of the Patterns of Potential Human Progress Series. Paradigm Publishers and Oxford University Press, Boulder, CO; New Delhi, India.

Hughes, B.B., Kuhn, R., Margolese-Malin, E.S., Rothman, D.S., Solórzano, J.R., 2014b. Opportunities and Challenges of a World with Negligible Senescence. Final Project Report to the SENS Research Foundation. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/Hughes_2014_SENS.pdf.

Hughes, B.B., Kuhn, R., Margolese-Malin, E.S., Rothman, D.S., Solórzano, J.R., 2015. Opportunities and challenges of a world with negligible senescence. Technol. Forecast. Soc. Chang. 99 (October), 77–91. https://dx.doi.org/10.1016/j.techfore.2015.06.031.

International Commission on Financing Global Education Opportunity, 2016. The Learning Generation: Investing in Education for a Changing World. United Nations, New York, NY. http://report.educationcommission.org/wp-content/uploads/2016/09/Learning_Generation_Full_Report.pdf.

Irfan, M.T., Margolese-Malin, E.S., 2012. SADC higher education futures 2050. In: Kotecha, P. (Ed.), Building Higher Education Scenarios 2025: A Strategic Agenda for Development in SADC. In: SARUA Leader Dialogue Series Vol. 3 no. 2. Southern African Regional Universities Association, South Africa, pp. 6–24.

Kuhn, R., Rothman, D.S., Turner, S., Solórzano, J., Hughes, B., 2016. Beyond attributable burden: estimating the avoidable burden of disease associated with household air pollution. PLoS ONE. 11(3)e0149669. https://dx.doi.org/10.1371/journal.pone.0149669.

Lee, J.-W., Lee, H., 2016. Human capital in the long run. Dev. Econ. 122, 147–169. https://dx.doi.org/10.1016/j.jdeveco.2016.05.006.

Marczak, J., Engelke, P., Bohl, D., Jiménez, A.S., 2016. Latin America and the Caribbean 2030: Future Scenarios. Background report for the Inter-American Development Bank by the Atlantic Council in collaboration with the Pardee

Center for International Futures. Atlantic Council, Washington, DC. http://www.atlanticcouncil.org/images/publications/Final_LAC2030-Report.pdf.

McCauley, D., 2014. U.S.-Iran rapprochement: a counterintuitive alternative to thirty-five years of distrust. Small Wars J. (January 19). Online journal, article available at, http://smallwarsjournal.com/jrnl/art/us-iran-rapprochement.

Milante, G., Hughes, B.B., Burt, A., 2016. Poverty eradication in fragile places: prospects for harvesting the highest hanging fruit by 2030. Stability: Int. J. Secur. Develop. 5 (1), 1–24. https://dx.doi.org/10.5334/sta.435.

Moyer, J.D., Bohl, D., 2019. Alternative pathways to human development: Assessing trade-offs and synergies in achieving the Sustainable Development Goals. Futures 105 (January), 199–210. https://dx.doi.org/10.1016/j.futures.2018.10.007.

Moyer, J.D., Firnhaber, E., 2012. Cultivating the Future: Exploring the Potential and Impact of a Green Revolution in Africa. African Futures Brief no. 4. Institute for Security Studies and Frederick S. Pardee Center for International Futures, Pretoria, South Africa; Denver, CO. http://pardee.du.edu/cultivating-future-exploring-potential-and-impact-green-revolution-africa.

Moyer, J.D., Hedden, S., 2018. How Achievable Are Human Development SDGs on our Current Path of Development. Paper submitted for publication (under review).

Moyer, J.D., Hughes, B.B., 2012. ICTs: do they contribute to increased carbon emissions? Technol. Forecast. Soc. Chang. 79 (5), 919–931. https://dx.doi.org/10.1016/j.techfore.2011.12.005.

Moyer, J.D., Porter, A., Johnson, S., Moyer, J.R., Bohl, D.K., 2015. Advancing Development in Uganda: Evaluating Policy Choices for 2016-21 and Selected Impacts to 2040. Research Paper prepared for United States Agency for International Development, Uganda Mission. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://pardee.du.edu/advancing-development-uganda-evaluating-policy-choices-2016-21-and-selected-impacts-2040.

Narayan, K., Donnenfeld, Z., 2016. Envisioning a Healthy Future: Africa's Shifting Burden of Disease. African Futures Paper no. 18. Institute for Security Studies and Frederick S. Pardee Center for International Futures, Pretoria, South Africa; Denver, CO. http://pardee.du.edu/envisioning-healthy-future-africas-shifting-burden-disease.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., et al., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42 (January), 169–180. https://dx.doi.org/10.1016/j.gloenvcha.2015.01.004.

Pearson, R., 2011. Using the International Futures global modeling system (IFs) for alternative scenarios by the numbers. Foresight: Int. J. Appl. Forecast. 22 (Summer), 13–19.

PricewaterhouseCoopers (PwC), 2016. El Futuro de la Alianza del Pacífico: Integración para un Crecimiento Productivo. PricewaterhouseCoopers, Alianza del Pacífico, Mexico. https://www.pwc.pe/es/publicaciones/assets/futuro-alianza-pacifico.pdf.

Rothman, D.S., Irfan, M.T., Margolese-Malin, E., Hughes, B.B., Moyer, J.D., 2014. Building Global Infrastructure. Vol. 4 of the Patterns of Potential Human Progress Series. Paradigm Publishers and Oxford University Press, Boulder, CO; New Delhi, India.

Scott, A.C., Solórzano, J.R., Moyer, J.D., Hughes, B.B., 2017. Modeling Artificial Intelligence and Exploring Its Impact. . Working Paper. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://pardee.du.edu/sites/default/files/ArtificialIntelligenceIntegratedPaper_V6_clean.pdf.

Shepherd, A., Mitchell, T., Lewis, K., Lenhardt, A., Jones, L., Scott, L., Muir-Wood, R., 2013. The Geography of Poverty, Disasters and Climate Extremes in 2030. ODI Report. Overseas Development Institute, London, UK. http://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/8633.pdf.

Shepherd, A., Scott, L., Mariotti, C., Kessy, F., Gaiha, R., da Corta, L., et al., 2014. The Chronic Poverty Report 2014–2015: The Road to Zero Extreme Poverty. Report of the Chronic Poverty Advisory Network. Overseas Development Institute, London, UK. http://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/8834.pdf.

Turner, S., Neill, C., Hughes, B.B., 2015. Guide to Scenario Analysis in International Futures (IFs). Scenario Analysis Manual 2015.06.23. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/2015.06.23_IFsDocumentation_Guide_to_Scenario_Analysis_v14.pdf.

United Nations Development Programme (UNDP), 2011. Sustainability and Equity: A Better Future for All. Human Development Report 2011. United Nations Development Programme, New York, NY.

United Nations Development Programme (UNDP), 2013. The Rise of the South: Human Progress in a Diverse World. Human Development Report 2013. United Nations Development Programme, New York, NY.

United Nations Environment Programme (UNEP), 2007. Global Environment Outlook 4 (GEO 4): Outlook for Development. United Nations Environment Programme, Nairobi, Kenya.

United States National Intelligence Council (U.S. NIC), 2004. Mapping the Global Future: Report of the National Intelligence Council's 2020 Project. National Intelligence Council, Washington, DC.

United States National Intelligence Council (U.S. NIC), 2008. Global Trends 2025: A Transformed World. National Intelligence Council, Washington, DC.

United States National Intelligence Council (U.S. NIC), 2012. Global Trends 2030: Alternative Worlds. National Intelligence Council, Washington, DC.

West, J.J., Smith, S.J., Silva, R.A., Naik, V., Zhang, Y., Adelman, Z., et al., 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. Nat. Clim. Chang. 3 (10), 885–889. https://dx.doi.org/10.1038/NCLIMATE2009.

Zurich Insurance Group, 2015. Overcome by Cyber Risks? Economic Benefits and Costs of Alternate Cyber Futures. Risk Nexus report in collaboration between Zurich Insurance, the Atlantic Council, and the Frederick S. Pardee Center for International FuturesZurich Insurance Group, Zurich, Switzerland. http://publications.atlanticcouncil.org/cyberrisks//risk-nexus-september-2015-overcome-by-cyber-risks.pdf.

CHAPTER

5

The Future of Human Development

Human development is about people—our number and our capabilities—and typically includes a special focus on health, education, and at least a basic standard of material wellbeing. This chapter examines the modeling of demographic change and the closely related human condition issues of health and education. Material wellbeing is considered in the next chapter, which turns to the future of economies and other more aggregate social systems.

5.1 POPULATION

There are probably no long-term global projections where there is less variation across analysts and methods than those of population. That is because of the relatively slow and most often regularly patterned change in its main proximate drivers—namely, fertility and mortality. That does not mean that modeling demographics is easy.

As in all issue areas that we discuss, it is possible to avoid demographic accounting and stocks and flows, focusing instead on identifying key variables and simply extrapolating them and/or making some basic assumptions about future patterns of change. For instance, the global population growth rate has been decreasing at a fairly steady pace since the early 1970s; it peaked at 2.1% annually in 1968 and had fallen to 1.6% by 1992 and to about 1.1% in 2017 (about a 0.5 percentage point decline every 25 years). Using simple linear extrapolation to estimate its reaching 0.6% by 2042 would not differ much from the forecasts of much more complex methodologies. Using that approach to forecast a growth rate of −1% early in the 21st century would, however, be much more questionable. The same would be true for extrapolative projections of reduction in infant mortality or increases in years of formal education attainment of adults, neither of which can presumably progress indefinitely along paths they have followed in recent decades. Were we to step back and simply try to extrapolate total population we would run into the problem that for many countries, and globally, it will almost certainly peak and then decline before the end of the century.

In addition to such problems of both linear and more complex extrapolative methods, many users of demographic scenarios want not only total population numbers but also information on the age and sex structures of the population because they affect important variables, such as the size of the potential work force and even political stability. More

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generally, detail on age and sex structures, births and deaths, urbanization level, mortality and morbidity patterns, and more can help refine both our understanding of demographic change and our explorations of its broader impacts.

In global modeling we are interested in the drivers of demographic change, the details of demographic structure and their close interaction with health and education, the forward linkages of all those aspects of human development to other human and natural systems, and then, ideally, closing the loop to represent the feedbacks to further demographic change.

5.1.1 Concepts, Structures, and Data

The basic demographic accounting equation is that population next year will be the stock of population this year adjusted by flows—that is, by adding births and net in-migrants and subtracting deaths. Demographers build most scenarios of future population (other than simple extrapolation of its total) with a cohort-component approach that represents the stock and the flows by age and sex. In that approach, when time steps are annual, births are determined from fertility of women at each age, deaths reduce population of specified age and sex, the remaining population ages by 1 year, and births enter the bottom of the population age structure. The age-sex cohort specification allows very useful visualization of demographic characteristics of a country or region; Fig. 5.1 portrays, in rolled-up 5-year categories, the possible population profile in 2030 of two countries with very different age-sex structures.

Fig. 5.2 shows the relationship between changing flow patterns and the changing total population stock, using a demographic transition framework (not a "theory" as it is sometimes called, at least until elaboration of the causal dynamics underlying it). This framework portrays pre-transition and traditionally poor societies as having high crude birth and death rates (crude because they are values per thousand across the total population and tell us nothing directly about values at particular levels of the age-sex structure). The demographic transition begins with crude death rate reductions that might be driven by factors such as improved hygiene and use of soap, cleaner drinking water, and technology (such as antibiotics). After a delay, birth rate reductions follow, due in part to family calculations that existing children will survive and also to social changes encouraging fewer offspring. The crude birth rate may eventually fall below the crude death rate, in part because as the population ages, deaths per thousand can actually rise even when longevity is increasing. The difference between the crude birth and death rates (e.g., $40/1000-25/1000=15/1000=1.5\%$) is the actual rate of net population growth, and it will peak (thereby creating an inflection point in the growth of the total population stock) in the middle of the transition.

In 2015, the crude death and birth rates (CDR and CBR) of the high-income countries of the world were 9.5 (beginning to rise) and 11.5 (quite stable). CDR and CBR of the low-income countries were 10.7 (falling) and 36.8 (falling). The high-income countries had essentially passed through nearly all stages of the transition (what happens next being uncertain since countries are moving into new territory), and the low-income ones were near the middle of the transition.

Although CDR and CBR help us understand the transition, they are highly dependent on the overall age structure of the population. Two other concepts, age-specific fertility rates and age-specific survival rates, are much more useful in forecasting because they are independent

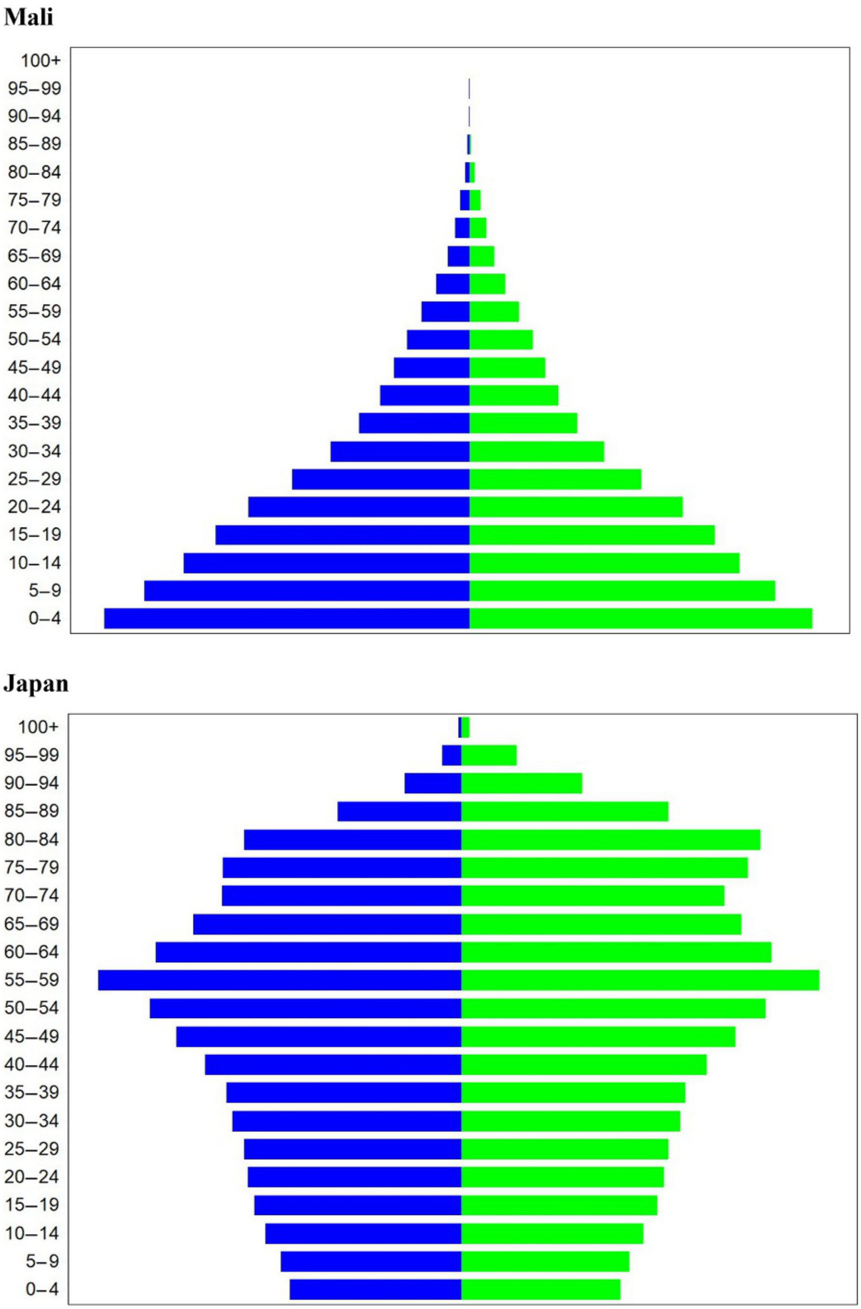

FIG. 5.1 **Illustrative country age-sex population structures in 2030: IFs Base Case scenario.**
Note: Population distribution (different country scales) of males (blue) and females (green) across age categories (vertical axes). Source: IFs Version 7.36, initialized with data from United Nations Population Division.

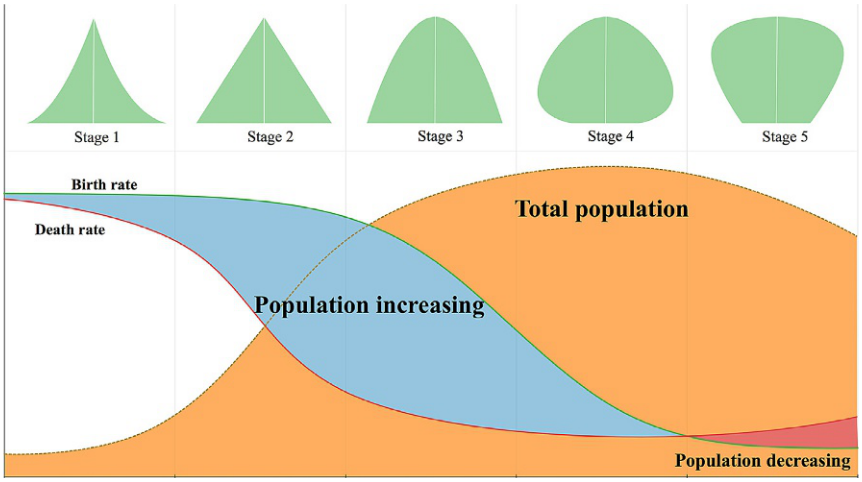

FIG. 5.2 **Stylized representation of the demographic transition of crude death and birth rates and resulting population growth.**
Note: Age-sex population structure representations for Stages 1–5 are highly stylized and somewhat exaggerated to show differences across the transition. Source: IFs project; patterned after a figure at Our World in Data (https://ourworldindata.org/world-population-growth) available through a CC BY-SA 3.0 license.

of that structure. A useful summary measure of the former is the total fertility rate (TFR), the number of live children the average mother will bear in a lifetime. Similarly, life expectancy at birth helps us understand overall mortality.

With respect to data, the United Nations Population Division releases new data (and alternative projection updates) on population, fertility, and mortality every 2 years. It does so in 5-year age categories, which it historically has provided up through a composite category age 85 and older.[1] Increasingly, with population aging, UNPD population and mortality (age-specific survivor) numbers range up to 100 years and older. Algorithms can spread the 5-year categories into 1-year categories (see UNDESA, 1956, p. 68 for an explanation of Sprague multiplier use). That spread is important when models like International Futures (IFs) advance through time with 1-year time steps. If the model maintained 5-year age categories for internal calculations rather than just in displays, as in Fig. 5.1, a change to numbers in one of the 5-year categories could inappropriately propagate into and through older categories very rapidly, a process referred to as numerical diffusion (Klanjscek et al., 2006, p. 417).

5.1.2 Demographic Transitions

In the modeling of demographic transitions, we turn to age- and sex-specific flows, namely births, deaths, and migration. Figs. 5.3 and 5.4 show the historical patterns of fertility and life

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[1] Those interested in very long-term regional and global population transitions (not including age-sex breakdowns) should see Maddison (2007, p. 376). He cites McEvedy and Jones (1978) as having estimated a global total population of three million in 7500 BCE (about the time of the Neolithic Revolution) and a rise to 170 million by 1 CE. Maddison picks up with estimation thereafter, and suggests that the climb took until 1820 to surpass one billion persons.

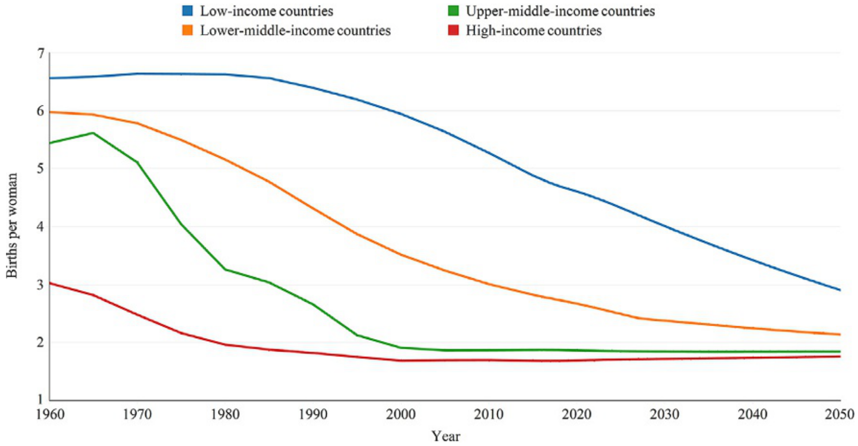

FIG. 5.3 **Total fertility rate by country economy classification: History and IFs Base Case scenario to 2050.** *Note: Uses World Bank classifications based on gross national income per capita. Source: IFs Version 7.36; historical data from United Nations Population Division.*

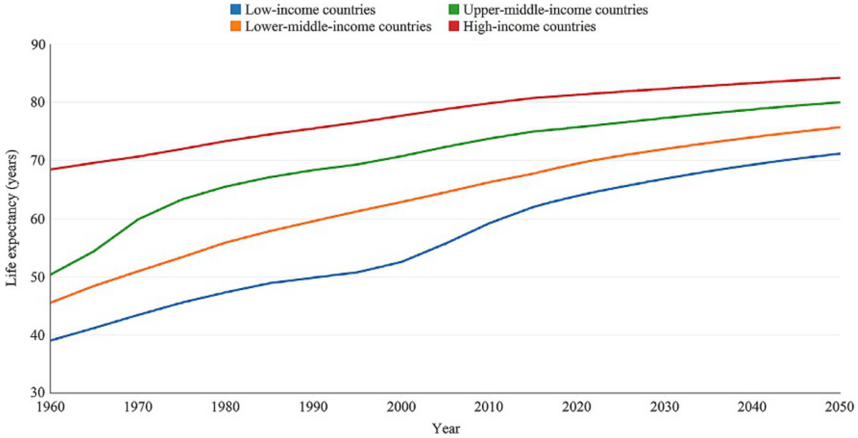

FIG. 5.4 **Life expectancy by country economy classification: History and IFs Base Case scenario to 2050.** *Note: Uses World Bank classifications based on gross national income per capita. Source: IFs Version 7.36; historical data from United Nations Population Division.*

expectancy since 1960 and in the IFs Base Case scenario to 2050 by World Bank country-income groups. The first figure shows that the transition to low fertility is basically complete in high-income and upper-middle-income countries, very far along in lower-middle-income countries, and clearly underway in low-income ones. The fertility rates in Central and Western Africa (not shown) are currently, however, nearly one-birth-per-woman higher than the already high rates in low-income countries generally, and the decrease has been minimal in recent years, making those subregions (and Eastern Africa to a lesser extent) the areas where uncertainty about population futures is greatest.

The second graphic shows both (1) the tremendous progress in reducing mortality, even in low-income countries where the AIDS epidemic has hit hardest, and (2) the convergence in life expectancy that has already occurred across countries and that, in the IFs Base Case, appears likely to continue.

Chapter 2 asserted that some model formulations are more important than others. Is that true in population? Sudden changes in mortality, such as AIDS- and Ebola-epidemic deaths or genocide, have sometimes greatly affected age-sex patterns and total population. And life expectancy at birth in low- and even lower-middle-income countries still has considerable headroom before converging to levels in higher-income countries. Yet, year-to-year changes in mortality rates are now relatively small in almost all developing countries relative to changes in fertility. Declines of fertility rates from six children per women to three or less have happened in one to two generations in a considerable number of countries, cutting the incremental impact on growth from births in half, and such declines may well happen in quite a few more countries. Fertility is the variable with the most power to shape demographic futures in low-income countries, as it once was in currently high-income countries.

Increasingly in high-income countries, however, fertility has become a less important variable because of low and quite stable rates. In richer and aging societies, changes in mortality patterns have very great importance for both total population size and forward linkages such as health and pension needs. We will therefore need also to pay considerable attention to important mortality dynamics, which the later discussion of the IFs health model will do.

Migration patterns have greatly affected population in situations such as the outflow from Ireland during the potato famine of the 1850s and the Russian/Ethiopian inflow to Israel in 1989–1993. The wave of settler population totally reshaped the demographics of the Americas following the European encounter with them. For most countries today, however, migration does not greatly affect population growth. Contemporary exceptions include shock-based events, such as the flow of migrants into countries bordering Syria and on to Europe in 2014–16. In Germany during 2015, the roughly 670,000 births were significantly overshadowed by the inflow of more than one million people; Hungary received three times as many per capita.[2] Other exceptions lie in persistent inflows, like those to the United States from its southern neighbors, to Australia from countries to its north, and out of a significant number of low- and lower-middle-income countries, especially conflict afflicted ones, where percentages have again been dramatic.

5.1.3 Modeling Population, Especially Fertility

Widely used demographic analysis systems all use variations of the cohort-component approach. This is true for those of the United Nations Population Division (UNPD), the Wittgenstein Centre for Demography and Global Human Capital in Vienna in association with the International Institute for Applied Systems Analysis, the US Census Bureau, and the Pardee Center for International Futures. Although such projects tend not to use the language that Chapter 2 introduced, they have generally developed methodologies that in some way combine distal formulations with proximate factors. The global demographic transition

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[2] See the BBC report on the "Migrant Crisis" (March 4, 2016) at http://www.bbc.com/news/world-europe-34131911.

to lower mortality and longer life expectancies, with the related progression from high-fertility to low-fertility status, provides the basis for the distal representations of demographic change, responsive at least implicitly to broad developmental forces such as advance in income, education, and technology. On top of that are country- and time-specific variations from the general patterns, driven by a variety of other, more proximate factors.

With revisions every 2 years, the UNPD produces national-level fertility, mortality, migration, and thereby total population projections, with a medium variant and alternative scenarios through 2100.[3] Use of the UNPD projections is extensive, including as exogenous inputs to many integrated assessment models (IAMs). Fundamentally important to the credibility of UNPD forecasts are the historical data available to the UNPD from country sources, updated and revised over time and supplemented with the work of the United Nations in filling holes and improving data (see UNPD, 2015 for a description of the methodology for both data handling and looking ahead).

The UNPD describes its approach to modeling fertility since the 2010 revision, and mortality since the 2012 revision, as probabilistic (UNPD, 2015, pp. 15–20). The project does not endogenously use independent variables (such as income levels) to generate country variations. Instead, it overlays country-specific fertility histories for seven 5-year cohorts between ages 15 and 49 years on the general global pattern of change. The process statistically generates and selects a median from a wide range of possible fertility and mortality futures using a Bayesian hierarchical model and double logistic functions[4] estimated from experience of all countries historically and each country's specific experience, weighting the former more heavily in earlier phases of the transition. The approach is able to represent the recent near stalling of fertility decline in some African countries, such as the Democratic Republic of the Congo and Tanzania.

Previous UNPD outlook revisions assumed an ultimate fertility rate of 1.85 in the low fertility phase, but in 2015 the United Nations allowed country-specific rises above the lowest rate of its heretofore final Phase 3, bounding them at 2.1. The high and low variants to the medium fertility scenario progressively increase or decrease birth rates relative to the medium variant, reaching a difference of 0.5 by 2025–2030.

With overlapping personnel and tools, the Wittgenstein Centre for Demography and Global Human Capital and the International Institute for Applied Systems Analysis[5] (hereafter WIC/IIASA, indicating the partnership) also produce very widely used population scenarios, including those for the new Shared Socioeconomic Pathways project (Lutz and KC,

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[3] The migration forecasting is least well developed.

[4] A Bayesian model uses prior knowledge like that for the global pattern across many countries, modified by new knowledge like the pattern to date of a specific country. A double logistic curve has an intermediate saturation at the inflection point. The UNPD approach requires six parameters to build country-specific double logistic functions representing high, medium, and low fertility phases of the transition.

[5] WIC is a collaboration since late 2010 of the World Population Program of the International Institute for Applied Systems Analysis (IIASA), the Vienna Institute of Demography of the Austrian Academy of Sciences, and the Demography Group and the Research Institute on Human Capital and Development at the Vienna University of Economics and Business. IIASA has had a demographic group since the early 1970s and its World Population Program has produced projections since 1990, including a major release in 2014, updated in 2018 (see http://pure.iiasa.ac.at/id/eprint/11143/).

2014; Lutz and KC, 2018). Based on work at IIASA by Lutz and colleagues going back to 1996 (Lutz et al., 1996), their approach has been probabilistic for longer than that of the UNPD, but also has significant differences (Lutz and Skirbekk, 2014).

The WIC/IIASA approach has moved beyond that of the UNPD by integrating broader human development with demographic analysis. Notably, it introduced multistate analysis that tracks people not just by age and sex but also by other conditions or states, most especially education level (building on Lutz and Goujon, 2001, and Lutz et al., 2007).[6] This integrated approach allows the multiple states to influence demographic flow variables (e.g., college-educated 25-year-old women differ on both fertility and mortality from those of the same age with less education).[7,8] A major foundation of the WIC/IIASA demographic and human capital approach was the building of a large-scale historical database (Goujon et al., 2016) to represent education attainment and mean years of schooling by age and sex for 171 countries from 1970 to 2010.[9]

The WIC/IIASA approach began with the age-sex-education structure of a basic or medium scenario. The approach, building on an algorithmic series of steps laid out in KC et al. (2010, pp. 397–398), used information gathered from experts on common patterns of change relative to the global pattern for low-fertility and high-fertility countries (differentiated by a TFR of 2.5) (see Fuchs and Goujon, 2014, pp. 204–210). The expert analysis came from an online questionnaire and process around its use that supported many hundreds of responses and several workshops in 2011. Total fertility rate projections for a medium scenario (KC et al., 2013, pp. 9–26) then combined global historical patterns in UN data with the generalized and country-specific expert judgment from the inputs gathered online and in meetings, bounding downward and upward movement at 1.75 children per woman, using the year 2200 for completion of upward convergence.

The education attainment structure was overlaid through an iterative process on a medium Global Education Trends scenario forecast. Fertility differences by age were linked to the scenario with special attention to the relative rates of fertility at different levels of education; higher education tends to lower and postpone child-bearing (KC et al., 2013, pp. 56–57). Therefore while education does not directly affect aggregate TFR in the medium scenario of the WIC/IIASA approach, changes in scenario assumptions about education attainment can generate alternative scenarios in which aggregate fertility, mortality, and migration patterns will vary, based on bottom-up calculations of age-sex-education cohort information in

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[6] The cohort component approach, and therefore the foundations for the multidimensional or multistate modeling approach, were developed at IIASA in the 1970s and early 1980s by Andrei Rogers, Nathan Keyfitz, and others (Rogers, 1975). See also Lutz et al. (2005), KC et al. (2010), KC et al. (2013), and Goujon et al. (2016) for continued development and application of the approach.

[7] It is programmed by Samir KC in R.

[8] O'Neill et al. (2010) also use a multistate approach and extend age and sex by urban–rural residence in iPETS, but for global regions rather than countries.

[9] Construction of this extensively harmonized and validated database drew on many sources, including the UNPD, the International Public Use Micro-Sample, UNESCO, national statistical agencies, Demographic and Health Surveys, Labor Force Surveys, and Multiple Indicator Cluster Surveys.

interaction with changing fertility, mortality, and migration.[10] (For more, see KC et al., 2010, pp. 406–413; Lutz and KC, 2014, Chapter 9.) On the basis of this approach, WIC/IIASA generated age-sex-education projections through 2100 in several scenarios including Global Education Trend, Constant Enrollment Rates, and Fast Track. Using this set of tools, the project also generated demographic and education projections for all five of the Shared Socioeconomic Pathway scenarios (see Section 3.3.2.1 on the SSPs).

A major update in 2018 (Lutz et al., 2018) built on the earlier work. Population and education data were extended to 185 countries and updated in support of a rebasing of projections from a 2010 to a 2015 start year (KC et al., 2018). Many of the expected patterns of longer-term change in key demographic variables such as fertility and mortality were maintained but connected to new base year values by interpolation. New tertiary education categories were added. Earlier scenarios were adapted and supplemented to create revised representations of three of the SSPs, namely SSP1, SSP2, and SSP3.

5.1.4 Population in IFs

Like the approaches discussed previously, demographics in IFs is cohort-component based, but key features distinguish IFs from other models. First is the endogenization in IFs of change in fertility and mortality. That is, scenarios of future population in IFs not only drive other variables from labor force size to food and energy demand but also are driven by variables ranging from income to education to rates of contraception use and smoking. A related difference from other forecasting systems is that scenario development in IFs, including that of its Base Case, does not involve either Bayesian probabilistic approaches or the use of experts to create country-specific patterns. Instead, initial conditions reflect past patterns in UNPD data as identified in the IFs preprocessor; alternative scenarios respond to changes in the driving variables from across the IFs models in interaction with parameters that model users can change. The attention to drivers differentiates between (1) deep, longer-term distal forces that undergird the demographic transition and (2) other forces reactive to country-specific and more immediate factors, many of which have policy relevance (like smoking rates).

The representation of population in IFs is structurally multistate. At its core, IFs represents population by age and sex, and it elaborates the age-sex matrix in two ways: first, by education enrollment rates of children and attainment of adults, again by age and sex, and second, by health condition (morbidity and mortality related to 15 death-cause categories), again by age and sex. Thus we can examine the education level of women in, for example, the 30–34 years age category (internal to the model, calculations track populations in single-year categories) and the number of men in the 60–65 years age category who die of cardiovascular disease. What is different from the WIC/IIASA approach is that IFs does not use education specific to age and sex to determine fertility or mortality of the cohorts (an analytical extension of multistate representations), but instead trades the detailed linking of age-specific

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[10] Although the WIC/IIASA approach builds upon a bilateral migration database, forecasting is biregional and linked to expert inputs; education of migrants is assumed equal to that of populations in their origin countries (Lutz and KC, 2014, p. 478).

education to age-specific fertility or mortality for the ability to draw easily upon additional drivers of those variables.

On the fertility side in IFs, a functional form embedded in algorithmic structure drives change in TFR in the aggregate within all scenarios, including the Base Case, rather than building TFR up from representations of fertility specific to age-sex cohorts. The formulations in IFs make country-specific TFR responsive to country-aggregate factors such as health (infant mortality) and contraception use as well as average education attainment of adults. IFs imposes aggregate top-down TFR on national fertility distributions rather than calculating them from the bottom up.

On the mortality side, IFs incorporates a large-scale health model, which the next major section in this chapter elaborates. Numerous distal and proximate factors (also identified later, and again country-aggregate) drive age-sex specific causes and rates of death, facilitating calculation of life expectancy from the bottom up. The reason for age- and sex-specific calculation of mortality rates (as opposed to the aggregate calculation of fertility rate) is obvious—age of death matters a great deal for forward linkages, such as size of labor force and elderly population. The representation of mortality is thus considerably broader with respect to both death causes and drivers in IFs than in the WIC/IIASA approach, but again does not have the linkage of age-specific education to age-specific mortality.

The IFs project's approach to migration exogenously uses projections from the United Nations and WIC/IIASA, allowing user choice across multiple scenarios. It now also includes endogenous formulations for gross bilateral migration that can supplant the exogenous specification of country-specific net migration (in both cases with normalization to assure global equality of immigration and emigration).

Because of fertility's critical importance in shaping alternative world demographic futures, the rest of this section focuses on it, with some consideration of mortality and migration as they interact with fertility to determine population size. The next major section of the chapter turns to a more extensive discussion of the modeling of health and mortality.

5.1.4.1 Fertility Rate

Three key variables drive IFs *TFR* forecasts over time (see Box 5.1 for conventions and notation used to describe variables, parameters, and equations throughout this volume). The first variable accounts for the change that typically accompanies long-term development and social evolution, including movement through the demographic transition. The two principal candidates to represent such distal change across all IFs models, not just the demographic model, are GDP per capita at purchasing power parity (*GDPPCP*) and the years of formal education attained by adults 15 years of age and older (*EDYRSAG15*). Our own analysis and that by others (e.g., Angeles, 2010) suggest that the latter is the stronger predictor for *TFR*.

In addition to long-term development and the deep or distal variables associated with it, fertility of societies is subject to short-term factors, most of which are in turn influenced heavily over time by the distal variables. These more proximate variables do, however, exhibit patterns of change that are at least somewhat independent of the distal drivers and more dependent on societal choices and policies. In the case of fertility change, two such variables are infant mortality (*INFMORT*) and the rate of use of modern contraception (*CONTRUSE*). If parents lose children to disease (or, as in Rwanda during 1994, to genocide), fertility rates will often be high or even rise to compensate for past deaths and in anticipation of future ones.

BOX 5.1

NOTATION IN EQUATIONS THROUGHOUT THIS VOLUME

IFs variable names appear in uppercase italics, while parameter names appear in bolded and italicized lower case. Variable names that appear in mixed case reflect intermediate calculations within the model code, but the intermediate variable names shown in equations may differ from those in the code.

Subscripts:

r is country/region (regions can be groups of countries or subregions within them)
c is age category/cohort
d is cause of death
e is energy type
f is food type
g is government spending sector
i is infrastructure category
l is land category
p is sex
s is economic sector
wd is water demand sector
ws is water supply sector
t is time, and will not generally be shown unless the equation involves more than one time-step, e.g., with a lag from the preceding year ($t-1$) or reference to initial conditions ($t=1$).

The availability and usage rates of contraception, often influenced by culture and sociopolitical choices, directly affect fertility.

The IFs fertility equation uses both infant mortality and contraception as proximate drivers, along with years of education of adults as a distal driver, in calculating TFR.

$$TFR_r = TFR_{r,t-1} * F\left(\ln\left(EDYRSAG15_{r,p=total}\right), LagInfMor_r, CONTRUSE_r\right) * \left(1 + (t-1) * \boldsymbol{ttfrr}\right) * \boldsymbol{tfrm}_r$$

The equation uses a lagged form of infant mortality. The lag is actually a moving average that in each time step averages 10% of the new value for infant mortality and 90% of the lagged value; the proportions are subject to change but capture roughly the 10-year lag-to-peak effect that Angeles (2010) identified.[11]

The additional term involving the parameter ***ttfrr*** represents change over time that is independent of the variable-driven relationship estimated via cross-sectional analysis with recent data. In fact, there has been global ideational and technological change with respect to fertility that the term can represent, something the IFs project characterizes as a "systemic shift" (discussed in Section 2.4.3.3). For example, when we plot data for TFR across countries against those for GDP per capita in 1960, 1980, and 2000 the lines move downward progressively—in 2000 the number of children expected at $5000 (in constant $2005) is about

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[11] We initialize the moving average with the value of the first year of the model run rather than with a value computed over an historical period preceding that first year. For this reason, the moving average changes slowly in initial years (values of early years tend to be very close to those of the initial value), with accelerating change over time up to about the 10th year. We therefore also phase in the effect of the moving average over 10 years.

three, compared to nearly five in 1960. The effect is largely absent with education attainment, which has itself systemically shifted upward relative to GDP per capita. Nonetheless, the time change parameter can be used for tuning. Finally, in the equation presented earlier, the user can adjust a multiplier parameter (***tfrm***) from its default value of one so as to force higher or lower fertility in sensitivity and scenario analysis.

In addition, there are three important algorithmic elements that wrap this equation in more extensive model code. First, in the model preprocessor we compute the historical growth rate of *TFR* (*TFRgr*) and use that to help drive year to year change in *TFR*. In fact, in the first year the change in *TFR* is fully driven by that internal variable, but attention to it is phased out over 10 years as the model formulations take charge. This approach, also used elsewhere in IFs (including urbanization rates; see discussion later in the chapter), helps protect inertial and/or country-specific elements of change and also helps prevent disruptive transients that make no logical sense and result in ugly history-plus-forecast graphics.

The second algorithmic element is that in the first year of the model forecast we capture the difference between *TFR* from the function and *TFR* from the data. This difference or shift factor[12] could be viewed as a country-specific fixed effect dependent on variables such as historical paths and cultural factors, and we could maintain it as a constant over time or simply as an error term. We choose, however, to phase it out over a fairly long period of time, specified by the parameter ***tfrconv***. Often in IFs the reduction of such country-specific shift factors is done over a half century or more, and, at the time of this writing, the parameter's value in fertility calculations was 100.

The total fertility rate is unlikely to shift indefinitely toward zero. In fact, unless life expectancies are growing, a society requires a value of about 2.1 simply to maintain a steady population. Thus the third algorithmic element bounds TFR by a minimum, which is specified parametrically (***tfrmin***) at 1.9 in the IFs Base Case as of this writing (in contrast to the higher and lower values of the UNPD and the WIC/IIASA analyses, respectively).

The use of modern contraceptives (*CONTRUSE*) is itself a function of a key distal driver, in this case GDP per capita at purchasing power parity (*GDPPCP*). The forecast level of contraception use depends also on an exogenous multiplier (***contrusm***) and on a temporal (*t*) upward drift in contraception use, related again to ideational change as well as to related technological innovation and diffusion (controlled by ***tconr***).

$$CONTRUSE_r = (F(GDPPCP_r) + t^*\boldsymbol{tconr})^*\boldsymbol{contrusm_r}$$

Once we have computed the total fertility rate, the number of births in a given year is a function of the country's fertility distribution across female age (which we converge over time to that of high-income countries), the age distribution of women, and the *TFR*.

A specialized research project with IFs (Hughes et al., 2015) explored the possible impact of dramatic advances in health that could affect the female fertility cycle. To do so, parameters were added to control the onset age of fertility (***hltfrageinit***), the peak age of it (***hltfragepeak***), the age of menopause (***hltfragestop***), and the rate of decline from peak to menopause (***hltfragehalflife***). If child-bearing age were greatly extended, it would necessarily lead at

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[12] Do not confuse country-specific "shift factors" with "systemic shift," which applies to relationships affecting all countries.

some point to a change not only in the peak age of child-bearing, but the rate of child-bearing at that age (***hltfrpeaklevel***), changed from current patterns at a rate controlled in the model by a final fertility parameter (***hltfrconv***). These parameters are not used in IFs Base Case analysis or even in most scenarios. They are present to allow scenario analysis of major disruptions in health and life expectancy.

5.1.4.2 Mortality and Migration

The second major flow that directly changes total size of populations is mortality. Earlier in the development of IFs the project relied on functions for life expectancy not unlike those for fertility, and then adjusted age-specific mortality with changes in life expectancy over time. Since our extended work on forecasting health in more recent years, we have replaced that approach with the health model documented later in this chapter.

With respect to migration, the third major flow that directly changes country-level population stocks, we are at an early stage of developing dynamic formulations; these formulations will need to respond to variables such as past patterns, differential population sizes, development levels, and domestic conflict. Currently we still rely upon projections from the United Nations and those from WIC/IIASA prepared in conjunction with the Shared Socioeconomic Pathways (SSP) project. Goujon et al. (2016, p. 343) indicated that the recent WIC/IIASA migration projections look to bilateral data from Abel and Sander (2014) but are biregional (connecting each country to the entire rest of world). Our Base Case also uses biregional, net migration.[13] We allow the user to select among alternative SSP or UNPD scenarios. To assure equal global sums of immigrants and emigrants, we normalize country values to the average of the two sums. Further, we have developed an option for turning to bilateral data and projections, additionally differentiating between voluntary and forced (e.g., refugee flow) migration.

According to data from the UNPD, the number of annual net migrants into high-income countries, the major destination group, grew from fewer than one million annually before 1970 to as many as five million in the early years of the twenty-first century. In SSP2 projections (the SSP set's Middle of the Road scenario), those stabilize at about four million annually until 2060 and then decline toward zero by century end.[14] Such a pattern logically represents diminishing push and pull factors as global incomes converge, population growth slows, and worldwide aging continues (young adults migrate with greatest frequency). This pattern is subject to major uncertainties, including attacks upon the globalization that supports migration and, alternatively, impacts of climate change that could increase pressure for it. Drawing on alternative SSPs in IFs helps frame such uncertainty.

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[13] Some economic models represent bilateral trade flows with "gravity" formulations that make them responsive to geographic proximity and economic size. Similarly, crude representations, building also on relative GDP per capita, could be used to create bilateral migration forecasts. They would, however, likely have limited credibility and utility.

[14] The UN Population Division (2015, p. 31) approach was to assume constant levels until 2045–2050 and then decline by 50% by 2095–2100.

5.1.4.3 Other Important Demographic Variables

Two of many other demographic variables of interest in global modeling are urbanization and household size because they (along with population aging) may affect other variables of interest to us, including energy, water, and food consumption patterns and therefore environmental impacts (O'Neill et al., 2010).[15]

In IFs we have not built forward linkages from urbanization rates because those rates generally remain secondary drivers of resource usage and environmental impact—nor do we differentiate urban and rural income levels. We do, nonetheless, forecast urbanization as a variable of great interest in its own right. Our approach is highly algorithmic, with three factors being especially important. The first is the past rate of urbanization, reflecting many deep drivers, such as population densities and policy influences (as in China in recent decades). A second factor is a slowing rate of urbanization as it approaches a maximum value (saturation) related to country-specific population density. A third element in the formulation is a cross-sectionally estimated function that gives us a general sense of the level of urbanization of countries at different levels of GDP per capita. That "target" value influences changes in the pace of urbanization from the historical rate to zero with ultimate saturation.

The formulation for household size in IFs is simpler. Change in household size from initial values is affected by the historical rate of change in interaction with change in the proportion of population that is less than the workforce entry age.

The description of demographics in this section has greatly simplified the model, but that simplicity is consistent with our desire to survey the tools involved in world model construction, including the accounting system, dominant relations, and secondary variables. For more complete documentation of demographics and other models in IFs, see the Pardee Center website.

5.1.4.4 Limitations

IFs computes total fertility rate from drivers, as discussed earlier, and imposes those on the endogenously shaped age structure of fertility, rather than building up to TFR from age-specific rates of bearing children. The advantage of this is that it facilitates driving change in TFR by a variety of variables from other models in the system, including education and infant mortality. A disadvantage is that it highly aggregates those linkages. Thus it does not utilize the multistate representation as fully as it might, for instance, through linking education by age-sex to fertility by mother's age rather than using aggregate education to drive total fertility.

We have also noted that IFs does not extend multistate representation of population beyond age, sex, education, and health to other potentially important variables, such as urban/rural residence. An explanation for this is that many of the deeper driver variables are highly correlated, as we noted for GDP per capita and education attainment; still, functional forms can always be enhanced.

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[15] A complication is that urban populations tend to have significantly higher average incomes than rural ones, and correlations of urbanization level with variables like per capita energy consumption may reflect those income differences rather than the concentration of population (Dodman, 2009). The creation of forward linkages from them should thus also consider income.

5.1.5 Comparative Scenarios

Fig. 5.5 shows global population scenarios from the UNPD 2017 revision medium variant, the WIC/IIASA 2018 revision of population in the SSP2 scenario (closest to a base case or medium variant of the SSPs), and the IFs Base Case.[16] The range of difference across the scenarios in 2100 is about 1.6 billion persons.

What are the sources of such difference in the core scenarios across projects? Fig. 5.6 helps explain the difference by showing the fertility rate scenarios for Western Africa, part of the Equatorial African belt where the fertility decline in recent years has been less pronounced than expected given rising levels of driving variables like income and education. Uncertainty about the persistence or reduction of that variance from expectations contributes to difference in global expectations. In their 2018 revision of population projections in SSP scenarios, WIC/IIASA recognized that infant mortality rates in the region have fallen more rapidly than earlier anticipated. As a key driver of fertility in their modeling and in that of IFs, downward revision of infant mortality is one factor leading to lower regional and global projections than the more inertia-based projections of the UNDP. Further, the projects differ with respect to assumptions about long-term fertility rates of countries with currently or prospectively low values; the ordering of global population expectations for 2100 in Fig. 5.5 is the same as that for the projects' fertility expectations.

There is, of course, a tendency for projects to compare methods, assumptions, and projections with each other, and some resultant tendency for adjustments to be in the direction of the output from others. While the position of the IFs Base Case scenario in the middle of the

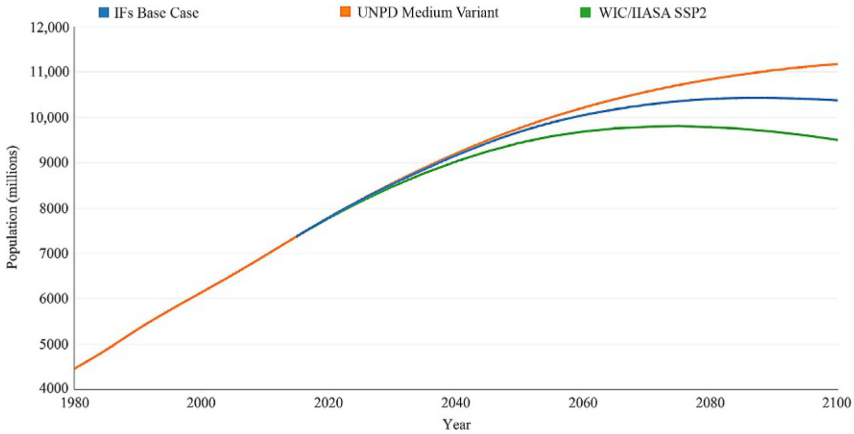

FIG. 5.5 **Global population: History and comparative middle variant scenarios to 2100.**

Source: IFs Version 7.36; historical data and UNPD scenario from the United Nations Population Division 2017 Revision; SSP2 revised projection (2015 base year) from WIC/IIASA (values courtesy of Anne Goujon and WIC/IIASA; see Lutz and KC, 2018 for elaboration of WIC/IIASA scenario).

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[16] See Hughes (2004) for a much earlier comparison of the IFs Base Case with projections from other projects across a wide range of issue areas.

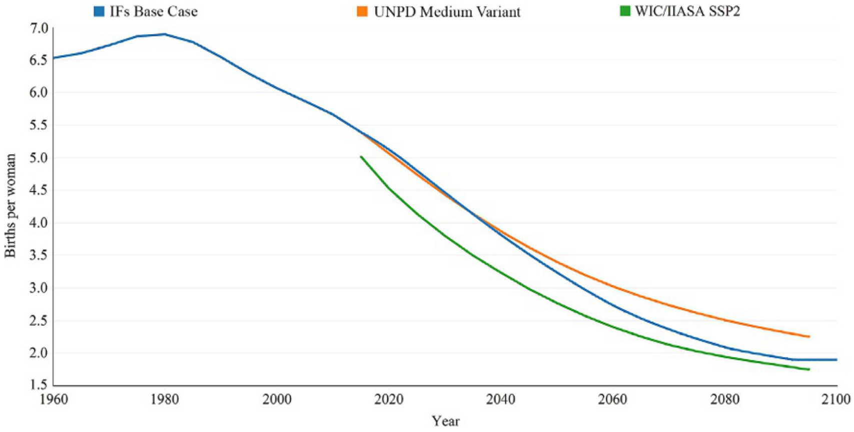

FIG. 5.6 **Fertility rates in Western Africa: History and comparative middle variant scenarios to 2100.**
Note: The discrepancy in the initial value for SSP2 is because UNPD and WIC/IIASA historical fertility data differ. Source: IFs Version 7.36; historical data and UNPD scenario from the United Nations Population Division 2017 Revision; SSP2 revised projection (2015 base year) from WIC/IIASA (values courtesy of Anne Goujon and WIC/IIASA; see Lutz and KC, 2018 for elaboration of WIC/IIASA scenario).

range in both Figs. 5.5 and 5.6 does not make the IFs forecasts better, it does confer some credibility (see Chapter 2 on model validation and accreditation).

Within projects, however, there is often much uncertainty about the future that such convergence of base or core scenarios does not communicate. For instance, Fig. 5.7 shows the range of population scenarios that the UNPD has produced, and by 2100 the variation across them is not just large, but extreme (from about 7.3 billion to 16.5 billion). The UNPD (2017, p. 3) identifies the range that is much more likely to be from 9.6 to 13.2 billion (with 95% certainty). The range of variation within the SSP scenarios in 2100 (Lutz and KC, 2018, p. 118) is also large (from 7.8 to 13.4 billion). Ideally, such wide ranges should help us understand the relative extent

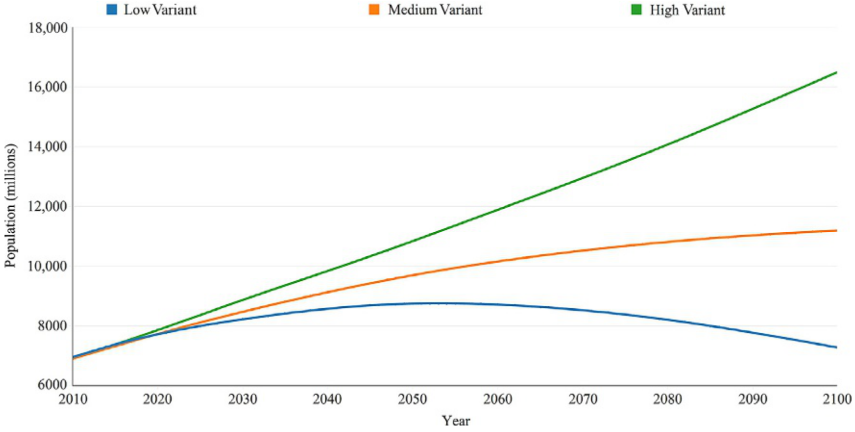

FIG. 5.7 **Comparative global population projections to 2100 across United Nations Population Division scenarios.**
Note: UNPD low, medium, and high variant scenarios differ only by fertility assumptions. Source: UNPD 2017 Revision.

of uncertainty around any given variable. In reality, analysts are justifiably concerned that almost no plausible future scenario be omitted. In addition, their ability to convey confidence in variations across the range is constrained because statistical techniques for identifying confidence intervals in very complex models have limited credibility.

5.2 HEALTH

Demographic analysis would seem mostly not to focus on health but rather on its absence, specifically on mortality. Yet as we move to modeling of health, we want more than total age-sex specific rates of mortality. Specifically, we want cause-dependent representation of mortality, minimally differentiating the communicable disease burden that drives most youth mortality from the noncommunicable burden that afflicts primarily adults and the elderly. Ideally, modeling would further (1) differentiate major causes within those categories, (2) represent significant numbers of distal and proximate drivers of mortality, (3) link changes in health not only to population dynamics but also to economics and government finance, and (4) explore a long time horizon. And we would like to know more not just about mortality, but also about morbidity (illness). As we shall see, these extensions are not at all common in demographic modeling. In fact, health modeling is itself scarce.

5.2.1 Concepts, Structures, and Data

Looking at females by country economy classification, Fig. 5.8 shows the J-curve form preferred by analysts of health for representing mortality rates by age and sex, laying the age-sex distribution on its side relative to Fig. 5.1.

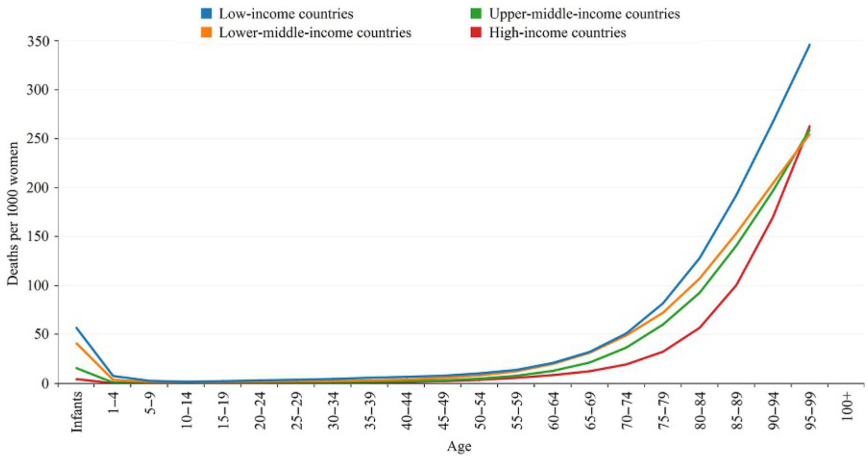

FIG. 5.8 **Age structure of female mortality (J-curve) by country economy classification in 2015.**
Note: Uses World Bank classifications based on gross national income per capita; no values displayed for 100+ cohort because mortality rates approach 100%. Source: IFs Version 7.36, using data from the Global Burden of Disease project at http://ghdx.healthdata.org/gbd-results-tool.

Data for such age-sex differentiation by cause of death are critical not only to medical practice but also to modeling health. In 1860, at the International Statistical Congress in London, Florence Nightingale proposed the development of a schema for systematic collection of hospital data. After some preliminary efforts, an international conference in 1900 released the first version of what has come to be called the International Classification of Diseases, revised roughly every decade since then and overseen by the World Health Organization (WHO). Version 11 was released in 2018. The sub-sub-categories are so numerous and detailed that one cannot help but wonder how well health professionals do in using them to record the morbidity and mortality they see—accidents and injuries include, for instance, being sucked into a jet engine, being bitten by a cow, and burns due to water skis being on fire.[17]

The Global Burden of Disease (GBD) project, begun in the early 1990s at WHO and now at the Institute for Health Metrics and Evaluation (IHME) at the University of Washington, has collected detailed data on mortality and morbidity going back to 1990. Its 2015 study covered 249 causes across 196 countries and many subunits of selected countries (GBD Mortality and Causes of Death Collaborators, 2016). Such detail of causes helps explain why the IHME releases clean, well-organized data on mortality by cause of death only with some delay, as does World Health Organization with the derivative Global Health Estimates (GHE). The IFs project received early access to several releases of GHE data due to the courtesy of Colin Mathers at WHO, but has now moved to direct use of IHME data.

5.2.2 Health Transitions

The demographic transition that Fig. 5.2 portrayed is associated with an epidemiological transition with a primarily communicable disease burden when death rates are high and a primarily noncommunicable disease burden when they are low. Omran (1971) identified three stages in that transition: (1) pestilence and famine, (2) receding pandemics, and (3) degenerative and manmade diseases. Consistent with that, Fig. 5.9 shows contemporary mortality patterns across the World Bank's country income-category groupings, providing insight into how mortality varies with development level. For example, whereas communicable diseases were responsible in 2015 for 54.8% of deaths in low-income countries, those diseases caused only 5.1% of deaths in high-income countries. Between 1990 and 2015, the ratio of deaths from noncommunicable diseases to those from communicable diseases more than doubled in middle-income countries and nearly doubled in lower-income countries. The share of deaths from injuries and accidents also is lower for upper-middle-income and high-income groupings. High-income countries provide insight into the future of global disease burdens, which will likely be overwhelmingly from noncommunicable causes.

On a global basis, 72% of deaths were already from noncommunicable diseases in 2015. In terms of disease burden, however, that is somewhat misleading because deaths from communicable diseases occur heavily at younger ages and noncommunicable diseases overwhelmingly afflict older populations. Thus each death from a communicable disease is responsible for more years of life lost relative to potential life expectancy than is each death from a noncommunicable disease. Only in the early years of the 2010 decade did global years of life

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[17] "Diagnostic Curiosity Shop," *Science News*, December 26, 2015: 4.

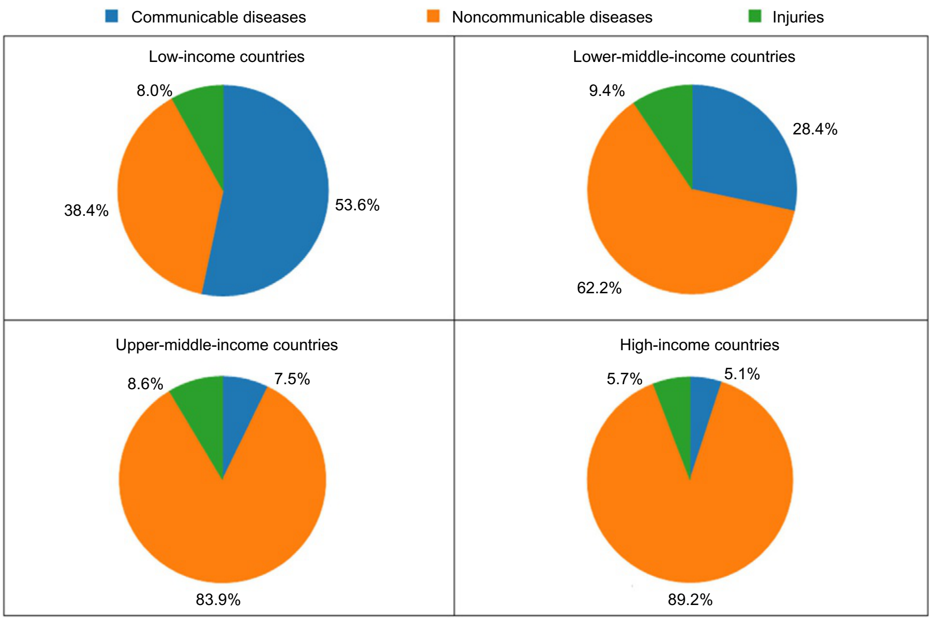

FIG. 5.9 **Mortality by major cause group and country economy classification in 2015.**
Note: Uses World Bank classifications based on gross national income per capita. Source: IFs Version 7.36, using data from the Global Burden of Disease project at http://ghdx.healthdata.org/gbd-results-tool.

lost from noncommunicable diseases surpass those from communicable diseases. Fig. 5.10 shows IFs Base Case forecasts of years of life lost globally in the three major disease categories. The rapidity of the shift to noncommunicable diseases reflects both progress against communicable ones and global population aging. Vehicle accidents drive much of the growing share of deaths from injuries, and autonomous vehicles could potentially disrupt that adverse trend.

5.2.3 Modeling Health, Especially Mortality

The United Nations Population Division (2015, pp. 21–29) uses changes in life expectancy by sex at birth to shape scenarios of mortality patterns without attention to cause of death. Parallel to its treatment of fertility, the UNPD's modeling of the progression from high to low mortality uses a double logistic function in a probabilistic analysis that represents a combination of global and country-specific experience. Decadal increments of maximum female life expectancy slowed from 2.5 between 1970 and 2005 to just 1.3 years between 2005 and 2015, and UNPD core scenarios anticipate about 1.25 years per decade going ahead.[18] Across

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[18] Taking a longer historical look, Vallin and Meslé (2010) presented data showing that female life expectancies at birth in longest-lived countries were relatively flat below 40 years until about 1790, grew by 11% through 1885, and experienced accelerated growth and added 32% through 1960 when growth began to slow. But longest country life expectancies for females older than 80 years has been growing steadily since the late 1800s and accelerated after about 1960 (attributed heavily to a cardiovascular revolution).

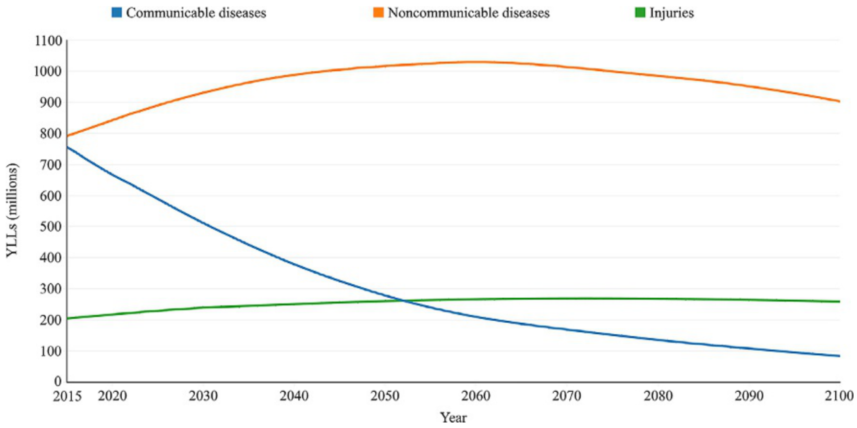

FIG. 5.10 **Years of life lost (YLLs) globally by major cause group: IFs Base Case scenario to 2100.** *Note: Using Japanese life expectancy as reference point for years lost. Source: IFs Version 7.36, initialized with data from the Global Burden of Disease project at http://ghdx.healthdata.org/gbd-results-tool.*

countries, male levels appear to converge to 4 years less than females as females reach 86 years. Countries with an historical experience of unusually high or low rates of change converge to leading countries in the region after reaching 60 years of age. Age-specific mortality is based on historical data when possible and looks to model life tables to fill holes and for patterns with high life expectancies. The UNPD uses specific assumptions for 21 countries with HIV prevalence exceeding 2.4%, with general assumptions of 90–95% treatment by 2050.

The WIC/IIASA multistate projection system is tied to a large-scale database (see earlier discussion in Section 5.3.1 of the WIC/IIASA approach to analyzing fertility and population). It calculates non-cause-specific mortality differences by education level, with a focus on life expectancy at age 15 years (hence, implicitly, it is more heavily responsive to noncommunicable than communicable disease). It looks to Japan as the leading-edge country for female life expectancy with anticipated extension through 2100 of 2 years per decade (Goujon et al., 2016, pp. 341–342). Regional forerunners converge toward Japan, and other regional countries converge to the forerunners. The WIC/IIASA system uses UNPD Medium Variant projections through mid-century for HIV-afflicted countries.

WIC/IIASA uses weighted averaging to combine the results of these data-driven processes with life expectancy values from expert inputs. An iterative process (see KC et al., 2013, p. 66) fits education-specific life expectancy variations to the total life expectancy so as not to change that total in the base scenario. The modeling thus does not change the medium population scenario but sets the basis for a bottom-up calculation of life expectancy from age-sex-education influences on mortality in alternative scenarios of education's advance.

A very important modeling thrust focused specifically on health (mortality and morbidity) was the work of Murray and Lopez (1996) and of Mathers and Loncar (2005, 2006a,b) in association with Global Burden of Disease activities at the World Health Organization. Murray and Lopez represented cause-specific mortality and disability (introducing disability-adjusted life years, or DALYs, as a combined measure of disease burden) for eight regions through 2020. Mathers and Loncar moved the work to the country level, extended the horizon to 2030, and incorporated additional causes of mortality and morbidity. Both GBD projects used education attainment, GDP per capita, and time (as a proxy mostly for technological advance) as key drivers, adding smoking for selected death causes. As mentioned previously, GBD work, including annual updated analyses of disease burdens, has continued at the University of Washington's Institute for Health Metrics and Evaluation,[19] and that initiative has begun to combine distal and proximate risk factor analysis in an approach similar to that of IFs, as will be discussed later. It has also taken the important step of making project code available on a GitHub site.[20]

Within integrated assessment modeling there have been some efforts to represent mortality from factors of special interest to that community, such as exposure to air pollution or the effects of weather volatility. Section 3.3.2 noted some movement to include climate change drivers of mortality (such as malarial deaths) in the integrated assessment models built to facilitate cost-benefit analysis of emissions controls. Another initiative, although as much in the tradition of world modeling as in that of IAMs, is the work of Hilderink and Lucas (2008) on the Global Integrated Sustainability MOdel (GISMO) of the PBL Netherlands Environmental Assessment Agency. At a global level GISMO endogenously represents three causes of mortality (malaria, diarrhea, and acute respiratory diseases), accounting for a significant percentage of global deaths of children younger than 5 years (Hilderink and Lucas, 2008, p. 59). The GISMO system took series on other mortality causes from the Global Burden of Disease work. Further, GISMO explicitly represents multiple drivers of mortality, both distal (GDP per capita and climate factors, notably precipitation and temperature) and proximate (child underweight prevalence, solid fuel use, and access to safe water and sanitation). In doing that, the model built on the experience of PBL with work on the TARGETS and IMAGE models (see Hilderink and Lucas, 2008, p. 32 and Ignaciuk et al., 2009, p. 25), as well as the PHOENIX population/health model. GISMO also includes some representation of education. Additionally, GISMO ties mortality back to its population projections with the cohort-component approach within PHOENIX.

5.2.4 Health in IFs

IFs aggregates all the GBD mortality and morbidity causes into 15 causes that cluster within its three main categories:

Communicable diseases: diarrheal diseases, HIV/AIDS, malaria, respiratory infections, and other communicable diseases.

Noncommunicable diseases: cardiovascular diseases, diabetes mellitus, digestive disorders, malignant neoplasms, respiratory diseases, mental health, and other noncommunicable diseases.

Injuries: intentional injuries,[21] vehicle accidents, and other unintentional injuries.

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[19] Work is underway at the Institute for Health Metrics and Evaluation to create a forecasting capability with a 25-year horizon (see https://www.fic.nih.gov/News/GlobalHealthMatters/january-february-2016/Pages/chris-murray-global-burden-disease-findings.aspx). Information from the project is limited.

[20] See https://github.com/ihmeuw/ihme-modeling.

[21] An IFs project supported by USAID is dividing intentional injuries into sociopolitical subcategories for further exploration.

The IFs formulations for age-sex specific mortality and morbidity draw on, combine, and extend previous modeling approaches. Extensive documentation of the health model is available on the Pardee Center website and in Hughes et al. (2011a,b), Kuhn et al. (2016), and Moyer et al. (2018).

5.2.4.1 *A Hybrid Distal and Proximate Modeling Approach*

Mortality and morbidity are highly related to deep or distal developmental factors. They are also driven by more proximate risk factors that respond in part to changes in the distal drivers (risks are to some degree intermediate variables), but also to country and time-specific factors, including policy decisions.

Therefore the IFs hybrid health model draws heavily on the earlier work of the Global Burden of Disease project, especially Mathers and Loncar (2005, 2006a,b) with its attention to distal drivers, and also on the World Health Organization's Comparative Risk Assessment Project with its focus on shorter-term risk factors. The IFs system then links projections of mortality and morbidity back to population dynamics and forward to the broader dynamics of development, including economic growth and government finance (treated in the next chapter).

The WHO Comparative Risk Assessment (CRA) project (Ezzati et al., 2004a,b) uses population attributable fractions (PAFs, the contribution of a specific risk to disease or death) to consider the extent of risk associated with factors such as indoor air pollution and body mass index relative to lowest possible levels of such risks.[22] Since typical and therefore expected risk levels across countries and time vary with the distal factors, it is the atypical risk level that modifies the distal driver foundation in IFs mortality formulations. Fig. 5.11 illustrates the hybrid distal/proximate approach graphically.

5.2.4.2 *The Distal Foundation*

At the core of its mortality computation, IFs relies on a regression function built on the structure of the earlier GBD project (Mathers and Loncar, 2005, 2006a,b). Age, sex, cause, and country-specific mortality rate is a function of four distal factors: income, education of adults, time, and (in specific cases) smoking impact.[23] In its work in other model areas, the IFs team has found that income and adult education attainment levels are so closely correlated across countries and time that formulations using both can be unstable, and generally only one is used in our model formulations. However, we follow the GBD's approach in this instance and use both. Time is significantly a proxy for technological progress, but can also represent other long-term trend change, as in behavior patterns. Smoking impact, a variable meant to capture historical smoking patterns, is included only in the modeling of mortality related to cardiovascular disease, malignant neoplasms, and

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[22] The CRA project has produced static estimates of risk for 79 risks, or clusters of them, affecting 315 causes of death over 25 years.

[23] We can consider smoking also as a distal variable in part because of an average 25-year lag with mortality. The IHME has moved to a distal driver approach that combines GDP per capita, education, and total fertility rate into an integrated social development index.

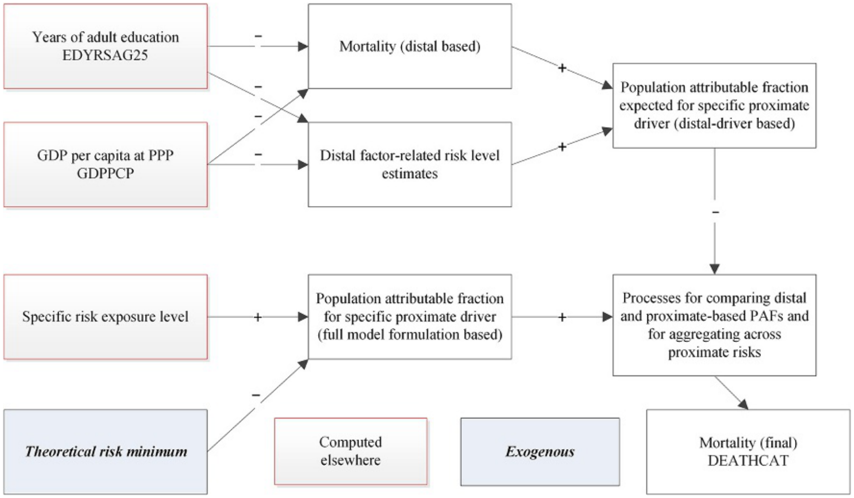

FIG. 5.11 **IFs representation of the relationship between distal and proximate drivers in determination of population-attributable fraction of risk and mortality rates.**
Note: White boxes represent variables in the IFs health model, gray boxes with red borders represent variables in other IFs models, and blue boxes represent exogenously specified variables. Source: IFs project.

respiratory disease.[24] IFs also follows the GBD approach by calculating a measure of morbidity, namely years of living with a disease, derivatively from annual mortality rates.

There are some disease-specific variations from the GBD approach in the IFs health model. For instance, IFs specifically represents HIV prevalence (a stock) and also AIDS deaths (a flow). However, the IFs accounting and forecasting system around HIV represents net change in that stock as a variable, without representing it as a function of incidence and termination (which would also facilitate a representation of prevalence by age and sex). IFs also includes a small structural submodel for vehicle deaths, tied to its forecasts of vehicle numbers and accident rates.

Using an historical database of mortality data from 106 countries for the years 1950–2002, Mathers and Loncar (2006a,b) calculated sex-specific regression coefficients for seven age categories (<5, 5–14, 15–29, 30–44, 45–59, 60–69, and 70+) and 10 major cause clusters.[25] GBD estimations using the data from the 106 countries created separate low- and high-income regression models (not coefficients for each country separately), with low income defined as GDP per capita

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[24] See Protocol S1 (Mathers and Loncar, 2006b) for more detail on the use of smoking impact in GBD projections.

[25] See Mathers and Loncar (2006b, p. 2) Protocol S1 Table 1 for the cause clusters used in the GBD 2002 and 2004 projections. IFs used their estimated coefficients for malignant neoplasms, cardiovascular disease, digestive disease, respiratory disease, other noncommunicable diseases, traffic accidents, unintentional injuries, intentional injuries, diabetes, and other communicable diseases. From the "other" noncommunicable disease category we broke out mental health for our own treatment (using a constant rate) and from the "other" communicable disease category we broke out diarrheal disease, malaria, HIV/AIDS (using our own structural model), and respiratory infections. Also, we re-estimated cardiovascular disease.

at purchasing power parity (PPP) < \$3000 in the initial year. Both sets of coefficients are publicly available.[26] IFs begins with the Mathers and Loncar formulation, including their notation.

$$\ln(M_{a,k,i,R}) = C_{a,k,i} + \beta_1 * \ln(Y_R) + \beta_2 * \ln(HC_R) + \beta_3 * (\ln(Y_R))^2 + \beta_4 * T + \beta_5 * \ln(SI_{a,k,R})$$

where

M is mortality level in deaths per 100,000 for a given age group a, sex k, cause i and country or region R
Y is GDP per capita
HC is total years of adult education (for adults 25 years and older)
T is time (year-1900)
SI is smoking impact

The final mortality formulation in IFs (*MFinal*) builds upon the IFs replication of the preceding GBD distal formulation of mortality (*MDistal*), but is more complex because it modifies the basic distal calculation in several ways. Namely, it (1) algorithmically spreads the cause-specific mortality from seven age categories to 20 five-year age cohorts, plus 100 and older, and then scales that spread to detailed death data from WHO using *ScaleFactors* computed in the base year, (2) normalizes the total mortality by age-sex to UNPD data in the base model year of IFs using *NormFactors*,[27] and (3) most important, modifies in future years the distal driver-based formulation of GBD as a result of specific risks and their impacts on specific causes of death, using a *RiskAdjustment* multiplier. The names in IFs for variables in the distal formulation (*MDistal*) are: GDP per capita at purchasing power parity (*GDPPCP*), years of adult education (*EDYRSAG25*), years lapsed since 1990 (*IY%*), and smoking impact (*HLSMOKINGIMP*).[28]

$$\begin{aligned} MFinal_{r,d,p,c} = {} & MDistal_{r,d,p,c} * ScaleFactors_{r,d,p,c} \\ & * NormFactors_{r,d,p,c} * RiskAdjustment_{r,d,p,c} * \boldsymbol{mortm}_r * \boldsymbol{hlmortm}_{r,d} \end{aligned}$$

where

$$\begin{aligned} MDistal_{r,d,p,c} = {} & \exp\big(\boldsymbol{MortFactors}_{r,d,p,c,1} + \boldsymbol{MortFactors}_{r,d,p,c,2} * \ln(GDPPCP_r) \\ & + \boldsymbol{MortFactors}_{r,d,p,c,3} * \ln(EDYRSAG25_r) + \boldsymbol{MortFactors}_{r,d,p,c,4} \\ & * (\ln(GDPPCP_r))^2 + \boldsymbol{MortFactors}_{r,d,p,c,5} * IY\% + \boldsymbol{MortFactors}_{\mathrm{r,d,p,c,6}} * \ln\left(\mathrm{HLSMOKINGIMP}_{\mathrm{r,p}}\right)\big) \end{aligned}$$

The final mortality equation allows scenario modification after the initial year with multiplicative parameters that change mortality overall (***mortm***) or by cause of death

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[26] For the GBD's regression results, see Tables S3 and S4, respectively, at https://doi.org/10.1371/journal.pmed.0030442.st003 and https://doi.org/10.1371/journal.pmed.0030442.st004.

[27] In the Base Case, we keep scaling and normalization factors constant, but we can control convergence of them to 1.0.

[28] While the health model presentation here is mostly true to variable and parameter names in IFs, there are a few exceptions to make understanding of more complex logic easier, including *ScaleFactors* and *NormFactors*. Also, MDistal in IFs code is *ModMorDstDet*. Further, the succeeding discussion of relative risk and population attributable fraction is stylized, again to assist readability.

(***hlmortm***). Not shown in the equation, ***hlmortcdchldm*** changes the rates of all communicable diseases for children aged 5 years and younger, while ***hlmortcdadltm*** affects rates of death from communicable diseases for adults aged 15–49 years.

The intercept and beta coefficients (***MortFactors***) in the distal driver equation are mostly from the Mathers and Loncar work (we did some estimation and search for reasonable values).[29] They are dimensioned by country/region *r* (differentiating only high-income or low-income countries), cause of death *d*, sex *p*, and age category *c*. For a few age categories and injury cause groups where regression analysis provided coefficients with low predictive value, we follow the GBD in keeping mortality rates constant over time instead of using the distal equations. Affected groups include: unintentional injuries for males older than 70 years; unintentional injuries for females older than 60 years; intentional injuries for males and females younger than 5 years; intentional injuries for males older than 60 years; and intentional injuries for females older than 45 years.

The key complication in the IFs final mortality equation is the calculation of the risk factor adjustment (*RiskAdjustment*) representing the impact of proximate drivers.

5.2.4.3 The Risk Assessment Overlay

Neither IFs nor any model will ever be able to represent all possible proximate drivers. Hence there is value in having an approach that combines the use of distal and *selected* proximate drivers, supplementing and adjusting the GBD distal-driver based approach and making the contribution of proximate drivers incremental to that expected given the configuration of distal drivers, thereby controlling for distal impacts. To explain how IFs does this, I first introduce concepts and terminology from the study of health risk as influenced by proximate risk factors.

We built our approach on an understanding of two basic concepts used in the WHO CRA project (Ezzati et al., 2004a), specifically *relative risk* (RR) and *population attributable fraction* (PAF). An RR is "A measure of the risk of a certain event happening in one group compared to the risk of the same event happening in another group."[30] We follow the approach taken by the CRA study, comparing our forecast population at risk to an "ideal" population with a "theoretical minimum" level of risk. For example, WHO estimates that children younger than five years old who are moderately or severely underweight are almost nine times more likely to die of communicable causes than a population of normal-weight children (Blössner and de Onis, 2005).

As its name suggests, a PAF or population attributable fraction reflects the degree to which a specific risk factor is associated with the occurrence of a specific health outcome. Formally, it is the proportional reduction in disease or death rates for the total population (including those with and without the risk factor) that we would expect if we reduced a particular risk factor to a theoretically minimum level (Ezzati et al., 2004a).

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[29] Almost all parameters in IFs are accessible through its interface; however, *MortFactors* can only be read from a file (hence the mixed upper and lowercase representation).

[30] Definition from the National Cancer Institute Dictionary of Cancer at https://www.cancer.gov/publications/dictionaries/cancer-terms?cdrid=618613.

$$PAF = \frac{\sum RR(x)*P(x) - \sum RR(x)*P'(x)}{\sum RR(x)*P(x)} = 1 - \frac{\sum RR(x)*P'(x)}{\sum RR(x)*P(x)}$$

where

$RR(x)$ is relative risk at exposure level x
$P(x)$ is the population distribution in terms of exposure level, i.e., the shares of the population at each level of exposure
$P'(x)$ is the theoretical minimum population distribution in terms of exposure level; for certain risks this is defined as no exposure; where this is not realistic, WHO defines an international reference population

Following common practice, we use distributions of risk exposure relative to the minimum level so as to benchmark the levels that different segments of the population face with respect to that minimum risk. Therefore, the steps for the preceding summations might be one, two, and three standard deviations below the level of access to nutrition (for example) for minimum risk. The value of PAF will generally be less than one because $P'(x)$ is normally less than $P(x)$, and the further the current situation is from the ideal, the closer the value of the PAF will be to one; the closer the situation is to ideal, the closer the PAF will be to zero.

Multiplying the mortality from a particular disease by the PAF yields an estimate of the number of people who would not have died had the risk factor been at its theoretical minimum level. If we assume that the values of $RR(x)$ and $P'(x)$ for specific risk factors and diseases do not differ across countries or change over time,[31] then changes in the PAF are solely a function of changes in $P(x)$, the exposure of the population to the particular risk factor. Thus it is necessary to be able to forecast the future levels of the risk factors.

Sometimes more than one risk factor will be linked to a particular disease. In theory, this requires estimating joint relative risks and exposure distributions. Under certain circumstances, however, a simple method can be used to calculate a combined PAF that involves multiple risk factors (Ezzati et al., 2004b, p. 2169).

$$PAF^{multiple} = 1 - \prod (1 - PAF^{i})$$

where

PAF^{i} is the PAF for risk factor i

The logic here is as follows: $1 - PAF^{i}$ represents the proportion of the disease that is not attributable to risk factor I, and multiplying these risks yields the share of the disease that is not attributable to any of the risk factors. Subtracting this product from one leaves the share of the disease that is attributable to the set of risk factors considered. For example, if we have two risk factors, the equation becomes:[32]

$$PAF^{multiple} = 1 - \left(1 - PAF^{1}\right) * \left(1 - PAF^{2}\right)$$

[31] The assumption is very reasonable for $P'(x)$ by definition. With respect to $RR(x)$, we assume these to be the same for all countries unless otherwise specified in the CRA reports. Any change over time is likely to be picked up in the other parts of our model that deal with changes in technology and the efficiency of health care systems.

[32] We decompose this equation in practice in the sequence of calculations by finding the individual PAFs, computing their individual independent effects with $(1 - PAF_{Distal})/(1 - PAF_{Full})$, and multiplying mortality independently and cumulatively.

TABLE 5.1 Risk Factors and Their Disease Impacts in IFs

Proximate Risk Factor	Diseases Impacted in IFs	Age Group Impacted in IFs
Body mass index*	Cardiovascular diseases Diabetes	30+
Childhood underweight* (includes effect of global climate change via its impact on undernutrition)	Diarrheal diseases Malaria Respiratory infections Other communicable diseases	<5
Indoor air pollution from household use of solid fuels*	Respiratory infections Cardiovascular diseases Malignant neoplasms Respiratory diseases	<5 25+ 25+ 25+
Smoking	Cardiovascular diseases Malignant neoplasms Respiratory diseases	30+
Unsafe water and sanitation*	Diarrheal diseases	All ages
Urban air pollution*	Respiratory infections Cardiovascular diseases Respiratory diseases	30+ 30+ 30+
Vehicle ownership and fatality rates	Road traffic accidents	All ages

Note: *The risk factors marked with an asterisk are treated with the relative risk approach described in the text in Section 5.2.4.3. Smoking enters via the term added to the GBD formulation for select diseases. Vehicle fatalities depend on a separate formulation driven only by proximate risk.*
Source: IFs project.

In IFs there are not a large number of diseases that are responsive to multiple risks that are also represented in IFs. Childhood diarrheal disease is one that is. The risk factor of undernutrition affects all communicable disease prevalence for children younger than 5 years old (except for HIV/AIDS with separate formulations in IFs), and the risk factor of unsafe water/sanitation affects diarrheal disease at all ages, including children—hence the overlap. Similarly, obesity and outdoor air pollution both affect the prevalence of cardiovascular disease in adults.

Table 5.1 identifies the proximate factors included within IFs. For a considerably broader list of potential risk factors, look to the WHO Comparative Risk Assessment project (Ezzati et al., 2004a, 2004b).[33]

5.2.4.4 *Combining the Distal and Proximate Risk Drivers*

At this stage in the modeling of mortality, we have an estimate from the distal formulation (*MDistal*) but still need to adjust that upward or downward to calculate *MFinal* based on the degree to which the supposedly more refined PAF_{Full} differs from PAF_{Distal}. We use the equation:

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[33] The CRA project has produced static estimates of risk for 79 risks, or clusters of them, affecting 315 causes of death over 25 years.

$$MFINAL = MDISTAL * \frac{1 - PAF_{Distal}}{1 - PAF_{Full}}$$

Using undernutrition as an example, if it is higher in the full formulation than in the distal formulation, PAF_{Full} will be larger than PAF_{Distal}. That will make $1 - PAF_{Full}$ smaller than $1 - PAF_{Distal}$ and their ratio larger than 1; the final mortality will thus be proportionately larger than that from the distal formulation.

Although we compute final mortality by age, sex, cause, and country as in the general GBD equation with which we started (and the details can be seen in the specialized displays of the model on mortality by age, sex, and cause and the mortality J-curve), an important model variable for display is *DEATHCAT*, which is total deaths by country/region, cause, and sex. This is the sum of the final mortality across age categories.

5.2.4.5 Other Important Health Variables

Infant mortality and life expectancy at birth follow directly from the mortality distribution that emerges in every country-year from the interaction of the distal drivers and proximate risk factors as discussed earlier.[34] So, too, does the calculation of YLLs for countries, which sums across all deaths the difference between age of death and the life expectancy of the globally longest lived same-sex population in any given year (currently Japanese).

A common measure of morbidity, and the one we use, is years of living with a disability (YLDs), summed across people and years. We took initial conditions of this from WHO data. IFs then initializes a ratio of YLDs to YLLs for the first model year. Following Mathers and Loncar (2006a), in subsequent years IFs calculates the percentage change in age- and sex-specific mortality from the previous year, and uses that to forecast the change in morbidity (an elasticity approach). The percentage change in disability relative to change in mortality (normally morbidity declines less rapidly) can be controlled by a parameter (***hlmorbtomortgthport***). As an example, the value of 50% for cardiovascular disease (***hlmorbtomortgthport*** = 0.5) suggests that morbidity decreases at half the rate of mortality. Malaria is set at 100% (1.0) in the Base Case, and other values informed by literature characterize other causes of death and morbidity. Given age- and sex-specific morbidity, the calculations to find YLDs are identical to those IFs uses for YLLs. Morbidity related to mental health is the one exception to this methodology; IFs computes an initial ratio of YLD/POP based on WHO data, keeping the ratio constant over time. Thus no progress in mental health morbidity is forecast in the Base Case.

Disability-adjusted life years (DALYs) are the sum of YLLs and YLDs (in IFs, see *HLDALY*, *HLYLD*, and *HLYLL*). We also compute these variables for the working-age population alone. Related to this is the computation of stunting. In the absence of data estimates around the world, we initialize the value for adult stunting by age and sex as a function of earlier child undernutrition; we advance it across time with aging and the addition of new youth stunting as a function of current undernutrition. Further, we represent severe acute malnutrition of children (*MALNCHPSAM*), which results frequently from political instability (but also from natural disasters, droughts, etc.). Severe acute malnutrition is more episodic than general undernutrition

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[34] Before there was a more developed health model in IFs, we did the reverse, calculating life expectancy as a function of distal driving variables and using change in it to adjust the mortality distribution.

and has a greater case-specific impact on stunting. Stunting rate of the working-age population (*HLSTUNTWORK*) has a forward linkage to productivity, discussed in Section 6.1.4.1.

Disease and health care have significant financial implications for society, but data on disease-specific public and private spending have been scarce cross-nationally (see GBD Health Financing Collaborator Network, 2017a,b for emerging data and forecasts). Hughes et al. (2014, Appendix 4) described the inclusion in IFs of disease-specific spending, drawing especially on data for the Netherlands and the United States, and of total public and private spending across countries from a variety of sources. *HLCOST* aggregates total national spending and *HLEXPENDPRIV* shows private spending. Chapter 6 describes the reconciliation of demand for government health spending with other demands and with revenue availability.

5.2.4.6 Limitations

First, although IFs incorporates a number of significant risk factors, the Comparative Risk Assessment Project identified many more that also could be used in analysis.

Second, a truly full representation of health would differentiate between the flows of disease incidence and termination (either through cure or death) and the stock that reflects disease prevalence, as in the distinction between the onset of diabetes and living with it. Although IFs moves in that direction with HIV/AIDS (incidence is still missing), available data are inadequate for a full incidence, prevalence, and termination model of health across large numbers of mortality causes.

Third, IFs represents the impact of aggregate values of both distal and proximate risk factors on mortality by age and sex, rather than representing the age- and sex-specific values of individual distal and proximate factors on that age-sex mortality (as WIC/IIASA do in their treatment of the impact of age- and sex-specific education on age- and sex-specific fertility and mortality). IFs does represent selected age-specific pathways—for instance, the relationship between child undernutrition and childhood mortality. It is, however, difficult to conceive of extending dynamic modeling of multiple cause mortality to age- and sex-specific risk exposure for all risks.

Fourth, on the forward linkage side, many potential linkages are missing. For instance, health of mothers affects children's education attainment, and that is not represented.

5.2.5 Comparative Scenarios

Fig. 5.12 shows the Base Case scenario of IFs for global life expectancy in the context of the UNPD Medium Variant and the original WIC/IIASA SSP2 scenario (2010 base year). IFs shows very nearly the same slowing of increases as does the UNPD; the pattern of rise from WIC/IIASA is quite linear and more optimistic. One reason for slowing global advance in IFs is that lower-income countries are narrowing the gap with higher-income ones, and countries at the leading edge experience slower rates of advance; thus convergence slows aggregate advance.

Because global patterns reflect both changes in life expectancy at the leading edge of wellbeing and also the convergence of less-developed to higher-income countries, it is useful to separate these effects and look directly at changes of life expectancy in the high-income countries. Fig. 5.13 does that. The figure simultaneously introduces some sense of the uncertainty in such forecasts by displaying all five of the SSP demographic scenarios from the

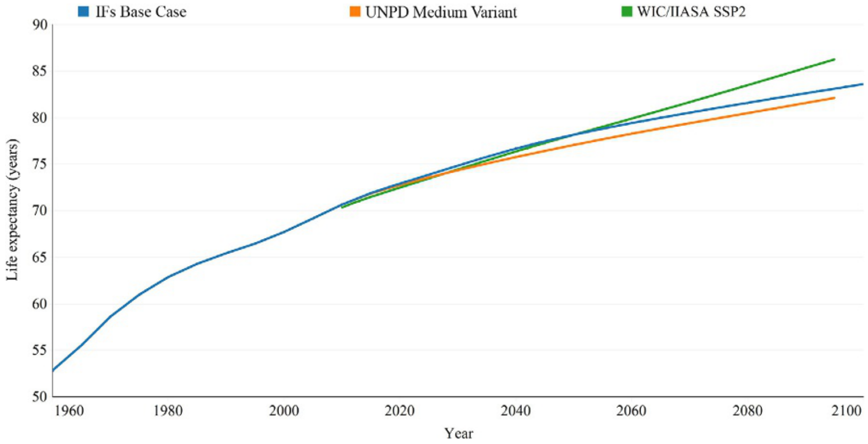

FIG. 5.12 **Global life expectancy: History and comparative scenarios to 2100.**
Note: Uses middle variant scenarios. The IFs and UNPD scenarios are nearly identical, causing overlap of their lines. Source: IFs Version 7.36; historical data and UNPD scenario from the United Nations Population Division 2017 Revision; WIC/IIASA original SSP scenario projection (2010 base year) provided courtesy of Samir KC and WIC/IIASA (at five-year intervals through 2095, filled by our interpolation).

WIC/IIASA project as well as the IFs Base Case. The SSP2 demographic scenario (used also in Fig. 5.12) shows a rise of high-income (and therefore leading-edge) life expectancy to over 95 years by 2100, more than the roughly 91 years in the UNPD Medium Variant scenario (not shown) and the 87.8 years of the IFs Base Case.

Explorations in subsequent sections of this book support the expectation of a slowing in the rise of two of the distal drivers in the GBD and IFs health formulations—namely, GDP per capita and years of education attainment. A concomitant slowing of rise in life expectancy would seem to have basis. Yet our formulation or parameters could be too conservative. For further context, based on an analysis with 21 models in GBD project work, Kontis et al. (2017) suggested that at the very leading edge there is more than a 50% chance that South Korean women will break the 90-year barrier by 2030 (IFs shows them at 86.5 years). The study points to that country's successes with inclusive improvements in economic status and social capital, childhood and adolescent nutrition, low body mass and blood pressure, low traffic accident and smoking rates, and universal health care.

5.3 EDUCATION

Sen (1999) and Nussbaum (2011) have elaborated the human capabilities approach to understanding of human development. In addition to being able to live a reasonably long and mostly health life, a key element that undergirds human freedom and wellbeing is education. Social opportunities require individual health and education as well as the economic opportunity and political freedom that are important topics of Chapter 6.

As stated previously, long-term modeling in nearly all issue areas, especially those around human and social development, benefits from considering GDP per capita and education

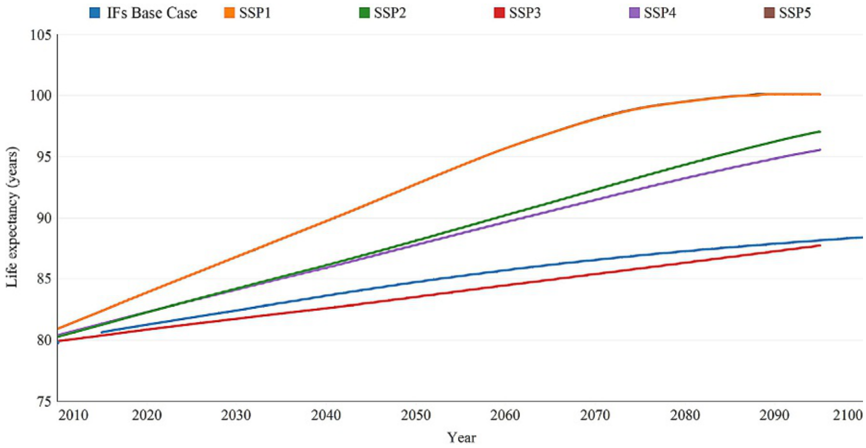

FIG. 5.13 **Life expectancy in high-income countries: Comparative scenarios to 2100.** *Note: Uses World Bank high-income group, and compares IFs Base Case with the original (2010 base year) WIC/IIASA Shared Socioeconomic Pathway (SSP) demographic scenarios. Despite very different story lines, the life expectancy projections from SSP1 and SSP5 are nearly identical for high-income countries, causing virtually complete overlap of their lines (see KC and Lutz, 2017 for demographic scenario descriptions). Source: IFs Version 7.36, initialized with data from the World Bank's World Development Indicators; original SSP scenarios of WIC/IIASA courtesy of Samir KC (at five-year intervals to 2095, filled by our interpolation).*

attainment as key distal drivers. Both long-term and shorter-term modeling benefit from the additional identification of important education-related policy interventions, including government spending or required school attendance. Although, as in other issue areas, extrapolation is an option in forecasting educational advance, using it would foreclose the analysis of such drivers that extended modeling facilitates.

5.3.1 Concepts, Structures, and Data

One basic accounting system in education is well known to all of us who have gone through a typical formal education system: enrollment in, progression through, and completion of successive levels of education.

There are actually two linked stock and flow systems of interest to modelers, however. The first represents that progression through the educational system. UNESCO developed an International Standard Classification of Education (ISCED) to identify sequential levels of educational systems and facilitate comparisons across countries. The most recent version, ISCED 2011, defines early childhood, primary, lower secondary, upper secondary, postsecondary non-tertiary, and four levels of tertiary education up through the doctoral level,[35] and the UNESCO Institute of Statistics provides historical data on the progression of students through these levels. The data distinguish net enrollment (that by of-age students) and gross enrollment (including also over- and under-age students). Because many developing countries have

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[35] See http://uis.unesco.org/en/topic/international-standard-classification-education-isced.

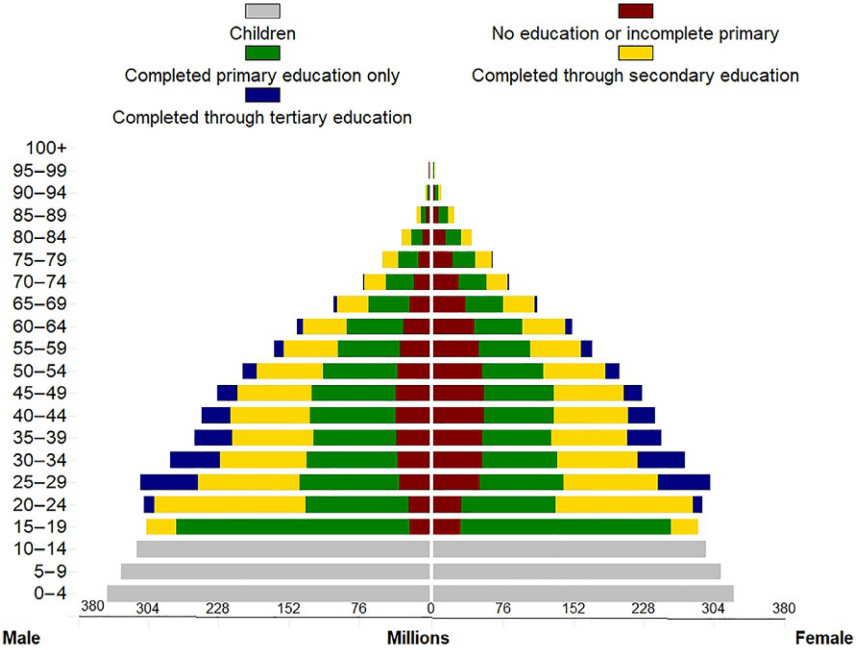

FIG. 5.14 **Global adult age-sex and education attainment structure in 2015.** *Note: Shows education attainment of those 15 years and older. Initialized with algorithmic spread across age categories (vertical axis) of education attainment data from Barro and Lee. Source: IFs Version 7.36, using data from Barro and Lee at http://www.barrolee.com and from United Nations Population Division.*

needed considerable time since independence from colonialism to establish effective statistical offices, those data were often quite incomplete but are now much less so.

When students age through the education system, they feed the structure that represents adult educational attainment, the second stock and flow system. Fig. 5.14 illustrates this second system by showing the endogenous overlaying in IFs of the stock of formal education in the world population on its age-sex structure. The pyramid shows the progression of the population through the aging process, with the adult population carrying its formal education attainment with it.

Although relatively easy to advance across time, this progression of education attainment across the years of adult life is difficult to initialize. Robert Barro and Jong-Wha Lee have been leaders in developing education datasets on both enrollment patterns and adult attainment, and they make the data freely available on their website.[36] Most recently those data cover gross enrollment patterns since 1820 and average education attainments of adults since 1870 (see Barro and Lee, 2015; Lee and Lee, 2016).[37]

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[36] See http://www.barrolee.com/.

[37] Barro and Lee (2015, pp. 12–13) built a dataset on gross enrollment for 89 countries since 1820 and, using that, constructed estimates of adult attainment since 1870. Lee and Lee (2016) indicate extension of the enrollment data to 111 countries. In addition, Barro and Lee have attainment values for 146 countries since 1950 at www.barrolee.com.

5.3.2 Education Transitions

Historical data collected and constructed by Barro and Lee (2015) allow us to see long-term transitions both in student enrollment patterns and in adult attainment (Figs. 5.15–5.17). We use their data extensively in this analysis of transitions and in IFs. It is quite incredible to think that in 1820, only about 7% of children were in primary school globally (only 25% even in currently high-income countries), and that 90% primary enrollment was not reached in high-income countries until about 1930 (about 1995 for developing countries). At the secondary level, high-income countries reached 90% just in 1995, and developing countries were still only at 80% in 2015. Fig. 5.15 shows the significant (but globally very uneven) progress at the primary level in the

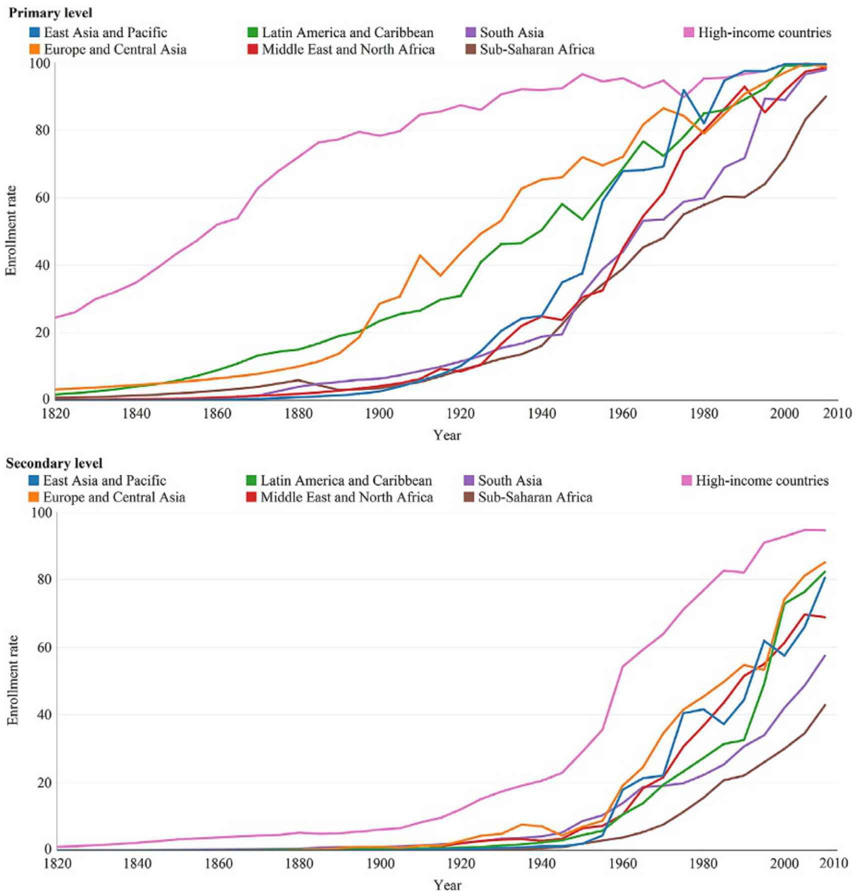

FIG. 5.15 **Primary and secondary education gross enrollment rates by country development level and region from 1820 to 2010.**

Note: Uses World Bank categories based on gross national income per capita. All named regions include only the low- and middle-income countries in those regions; high-income countries from all regions are grouped together. Source: IFs Version 7.36, using data on adjusted gross enrollment supporting Barro and Lee, 2015 and Lee and Lee, 2016 at www.barrolee.com.

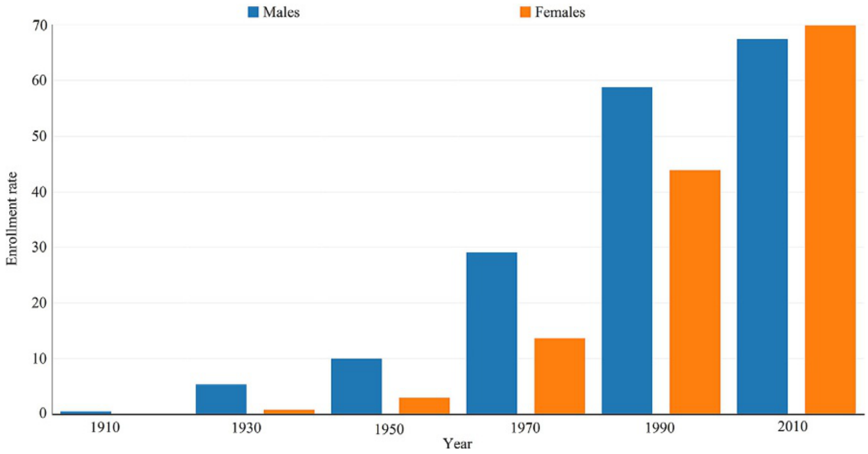

FIG. 5.16 **Male and female secondary gross enrollment rates: Middle East and North Africa from 1910 to 2010.** *Note: Values are for low- and middle-income countries in the World Bank's Middle East and North Africa region. Source: IFs Version 7.36, using data on adjusted gross enrollment supporting Barro and Lee, 2015 and Lee and Lee, 2016 at www.barrolee.com.*

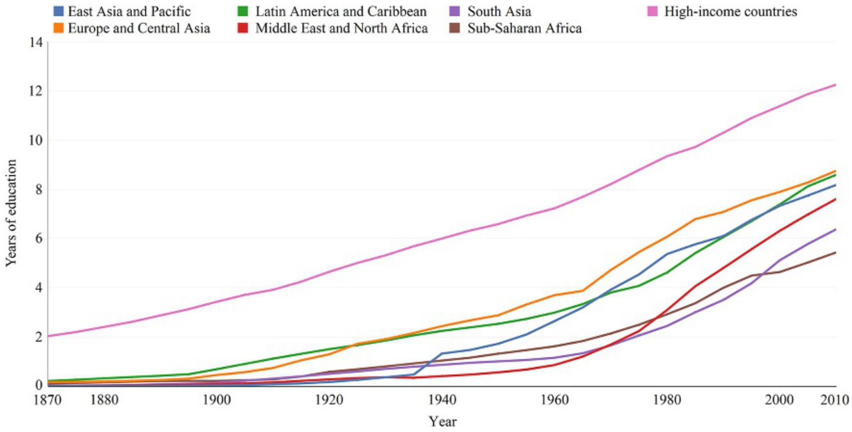

FIG. 5.17 **Years of education of adults age 15–64 years by country development level and region from 1870 to 2010.**
Note: Uses World Bank categories based on gross national income per capita. All named regions include only the low- and middle-income countries in those regions; all high-income countries are grouped together. Source: IFs Version 7.36, using data on adjusted gross enrollment supporting Barro and Lee, 2015 and Lee and Lee, 2016 at www.barrolee.com.

19th and 20th centuries and, building on the base this created, the very rapid and much more widely distributed progress at the secondary level in the late 20th century.

Enrollment patterns have often significantly differed for males and females, with higher (sometimes much higher) historical rates for males. Fig. 5.16 traces the gender pattern in secondary enrollment rates over time in the Middle East and North Africa. That graphic indicates the progress that females have recently made in closing the gap, a phenomenon that we can see across education levels and around the world. For instance, at the tertiary level in high-income countries, female enrollment rates now exceed those of males by nearly 13% (by 4% globally)—some of which represents the return to education of older women who did not earlier have and/or perceive the opportunity.

Moving attention from enrollment to education attainment, in 1870 the average traditional working-age adult (15–64 years) probably had only about 0.6 years in formal education—and in more advanced countries, only 2.1 years. By 2010, the level had reached 7.4 years in developing countries and 12.3 in high-income ones. Although the progress shown in Fig. 5.17 does not yet indicate any pattern of saturation, we know that, especially in high-income countries, levels will begin to flatten in coming decades because primary and secondary enrollments have been universal for some time and tertiary enrollment rates must also eventually peak.

Steady movement in this century toward closure of education gaps across global country groupings appears very highly probable. To understand country differences, education forecasting will increasingly need to turn to issues of quality and lifelong learning.

5.3.3 Modeling Education Progression

The two interacting stock and flow systems (progression of students and levels of education attainment of adults) frame alternative approaches to modeling education.[38] One approach is to represent endogenously the flow of students through the education system, to use the outflows to populate the stock of education attainment for the youngest in the adult population, and to advance that stock through the population as it ages. Wils (2007), discussed also in KC et al. (2010, p. 391), built on earlier work at IIASA and used that approach in work at the Education Policy and Data Center. IFs also uses this approach.

A second approach is not to model the dynamics of change in the student flows across levels in the education system, but rather to project the total education attainment of young adults and feed that into the progression of adult attainment as they age. One can combine the second approach with alternative exogenous scenarios concerning the education attainment of the youngest adults. This is the current WIC/IIASA approach (Lutz and KC, 2014). The Global Education Trend scenario, combined with the medium demographic forecast, is WIC/IIASA's medium or "most likely" education scenario. It uses a Bayesian model tied to the last 40 years of data to estimate progression of education attainment rates for young adults to higher levels over time. In addition, the project built Fast Track, Constant Enrollment Rates, and Constant Enrollment Numbers scenarios. In the first, advance of education attained by age 30–35 years (when formal education is assumed to be complete) expands like that of South Korea and other East and Southeast Asian countries historically. More recently these scenarios were adjusted so as to map to three of the SSP scenarios; SSP2 is based on Global Education Trend, SSP3 is tied to Constant Enrollment Rates, and SSP1 is a revamped Fast Track scenario, modified to achieve the education Sustainable Development Goal (KC et al., 2018, p. 27).

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[38] On forecasting education and its broader social impacts, see also Bruns et al., 2003; Cuaresma and Lutz, 2007; Delamonica et al., 2001; KC et al., 2010; Lutz and KC, 2014; Lutz and KC, 2013; McMahon, 1999; and Wils and O'Connor, 2003.

Whichever approach is taken to populating the bottom of the adult age and education representation, additional modeling choices are needed with respect to the aging of the population at different education levels and the implications of education for fertility and mortality. As we discussed in Section 5.1.3, the approach of WIC/IIASA (Barakat and Durham, 2014; KC et al., 2010; Lutz and KC, 2013; Lutz et al., 2018) has been to build alternative scenarios in which change in education attainment of young adults is effectively exogenous (with education attainment aging with the associated population cohorts), but fertility and mortality projections benefit from information on age- and sex-specific education levels. In contrast, IFs represents childhood education enrollments endogenously, but does not use the information that its population cohort structure carries on age-sex education levels through adulthood in its calculation of fertility and mortality. Instead, as discussed earlier, IFs uses aggregate country levels of education attainment in combination with other variables to drive both fertility and mortality.

5.3.4 Education in IFs[39]

The IFs education model represents primary, lower secondary, upper secondary and tertiary levels of education, with young adults then advancing into and through the education attainment structure of the total population.

The basic data on student flows come from UNESCO's Institute for Statistics online repository, supplemented by data on tertiary education from the Organisation for Economic Co-operation and Development (OECD). The preprocessor of IFs makes estimates for countries with missing data, generally using cross-sectionally estimated functions from GDP per capita at PPP. The preprocessor also uses algorithms to reconcile incongruent data values and compute important intermediate variables for dynamic forecasting, such as primary survival rates (the progression of students to the last year of primary education). With respect to attainment, in the model's base year the system spreads education attainment data from Barro and Lee across the entire age-sex structure, using an algorithmic system that recognizes the increasing levels of attainment of younger populations.[40]

IFs representation across time involves year-to-year entry into, and grade-flow progression through, the primary level by of-age (net enrollment) and all-age (gross enrollment) students. Gross enrollment includes "above age" students, a category that can be sizeable in lower-income countries struggling to provide universal education for all citizens. The system also computes survival rate of gross entrants to, and gross completion of, final grade.

The grade flows at the lower secondary and upper secondary levels are of gross enrollment. Aggregation across the grades provides the enrollment rate. An analytical function estimates total net secondary enrollment from gross. The model calculates the vocational share at both lower and upper secondary levels, using initial year rates and allowing scenario variation of them that can affect the forward linkage to multifactor productivity (see Section 6.1.4).

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[39] Mohammod Irfan developed the original education model of IFs (Irfan, 2008) and has continued to refine and extend it over many years. See additional documentation on the Pardee Center website.

[40] The algorithm was developed after discussion with T-21 modelers, especially Weishuang Qu, at the Millennium Institute.

The previous year's enrollment rate and GDP per capita drive the upper secondary graduation rate. Intake and graduation allow calculation of the dropout rate. Upper secondary completion rates and GDP per capita drive the tertiary intake rate.

Specification of variables that control student flows (intake, progression or dropout, survival to final year, completion, and transition to subsequent levels) involves all of the following:

(1) the historical conditions of each country;
(2) typical global patterns in relationship to income levels, while also recognizing the global push for more education independent of those levels; and
(3) interaction between demand for more education with financial capabilities of governments facing competing pressures for expenditures (see government finance in Section 6.1).

The pass-through of education years to adult attainment takes into account completion rates at all levels (times years of enrollment in each level), plus years within levels prior to dropout for those not completing. IFs advances the adult education attainment structure across time with the age-sex structure, feeding the bottom of it by young adult attainment information from the enrollment progression system.

With respect to forward linkages, beyond the impacts of aggregate adult education attainment on fertility and mortality/health outlined earlier in Sections 5.1.4 and 5.2.4, IFs has linkages from attainment to productivity, governance, and other variables as discussed throughout this volume. Along with GDP per capita at PPP, aggregate education attainment is one of the key distal or deep developmental drivers across models in the IFs system.

5.3.4.1 *Primary Intake*

IFs education equations can be illustrated with a focus on one of the most targeted variables in recent decades, the net intake rate of students into the primary level (*EDPRIINTR*). The structure of that formulation is tied to GDP per capita at PPP (*GDPPCP*), adjusted by a country-specific shift factor that compares the expected value from the formulation with the data value in the country in the initial year (*EDPriIntNShift*). As often in IFs forecasting, we converge this initial shift factor toward zero over ***priintn_shift_time*** years, recognizing the tendency for countries to have similar development patterns in the long run. The convergence is very slow when countries are above values expected in the function and, recognizing the impetus given to primary education globally, quite rapid when values are below expectations. In the resulting equation, "*p*" indicates sex (see again Box 5.1 for notation conventions).

$$EDPRIINTNBase_{p,r,t} = CalEdPriInt_{p,r,t} + ConvergeOverTime\left(EdPriIntNShift_{p,r,t=1}, 0, \boldsymbol{priintn\_shift\_time}\right)$$

where

$$CalEdPriInt_{p}, r, t = F(\ln GDPPCP_{r,t})$$

$$EdPriIntNShift_{p,r,t=1} = EDPRIINTN_{p,r,t=1} - CalEdPriInt_{p,r,t=1}$$

Between 1992 and 2000, the regression line of net intake with GDP per capita shifted upward by about 10 percentage points, reflecting the greater emphasis on primary education during that period, both globally and within countries around the world (see again Figs. 5.14–5.16). In contrast to the unique shift factors of countries relative to the global pattern in the forecasting formulation, we refer to this change in basic underlying dynamics as "systemic shift" (see the discussion of building dynamic model formulations in Section 2.4 for more on shift factors and systemic shift). This annual systemic shift factor (*CalEdPriIntFac*) is added to the basic primary intake rate to calculate an adjusted intake value (*EDPRIINTN*).

$$EDPRIINTN_{r,p,t} = EDPRIINTNBase_{r,p,t} + CalEdPriIntFac_{r,p,t}$$

where

$$CalEdPriIntFac_{r,p,t} = \frac{\mathrm{t}-1}{SS\_Denom} * \left(CalEdPriInt2_{r,p,t=2000} - CalEdPriInt1_{r,p,t=1992}\right)$$

$$CalEdPriInt1_{r,p,t=1992} = f_1\left(GDPPCP_{r,t=1992}\right)$$

$$CalEdPriInt2_{r,p,t=2000} = f_2\left(GDPPCP_{r,t=2000}\right)$$

$$SS\_Denom = \mathrm{AMAX}(10, \mathrm{AMIN}(20, GDPPCP_r * 10))$$

The modeling of primary intake in IFs provides a general sense of the approach to specification of other important variables, including survival to final year and transition to higher levels of education. The logic at higher levels of education is similar to that at the primary level. One additional important variable, calculated in IFs from enrollment rates of students across all years, is the number of expected years of schooling for an elementary entrant (*EDYRSSLE*). This variable is used in the calculation of the United Nations Development Programme's Human Development Index, discussed in Section 5.4.

5.3.4.2 Education Financing Reconciliation

Wishes for universal primary or secondary education cannot make it so. Budgetary constraints play a role. Hence the desired intake levels are subject to further adjustment (most often, unfortunately, downward, but sometimes upward) by the modeled allocation of spending to education. The next chapter will discuss the government finance model as part of the broader IFs socioeconomic system structure. Here we note only its interaction with education.

The interaction of education and finance begins with a calculation of the per-student expenditure demand as a percentage of GDP per capita. Personnel costs are the biggest item in education budgets, so per-student expenditure rates correlate strongly with GDP per capita. The illustration here is for the primary level (*EDEXPERPRI*), but such functions have been estimated at all levels and costs per student rise across levels, becoming especially high at the tertiary level. Again, we initialize the model with country-specific shift factors and converge those to zero over the long run. A parameter (***edexppconc***) controls the years required for shift toward values expected as a function of GDP per capita at PPP.

$$EDEXPERPRI_{r,t} = CalExpPerStudPri_{r,t} + ConvergeOverTime1\left(EdExpPerPriShift_r, 0, \boldsymbol{edexppconv}\right)$$

where

$$CalExpPerStudPri_{r,t} = f(\ln(GDPPCP_{r,t}))$$

$$EdExpPerPriShift_r = EDEXPERPRI_{r,t=1} - CalExpPerStudPri_{r,t=1}$$

The total expenditure need for the desired enrollment at all levels is pushed upward to the government finance system, where it competes with other demands and also is reconciled with forecast long-term revenue streams. That system provides a total education expenditure value back to the education model.

The adjustment of the modeled education spending to the available funds has three steps. The first step involves nudging spending per student toward patterns expected at each country's level of GDP per capita. That is, if excess funds are available and countries are underspending, per-student spending is increased marginally (about 2% of the difference each year, a value based on tuning model behavior to historical patterns); if funds are in deficit and countries are overspending relative to global patterns, annual decreases (again marginal) are made in per-student funding.

In the second step, spending adjustments affect flow patterns at each level of education—for instance, at the primary level where they affect intake and survival rates. A budget impact ratio is computed from funding obtained (*CalcTotSpend*) divided by funding demanded (*CalcTotCost*). That ratio increases or decreases the projected student flow rates. The algorithm of impact is nonlinear, because changes in most flows exhibit S-curve behavior over time, with most rapid change near their inflection points and, of course, slow change (upward or downward) as they reach saturation (100%).

The two algorithmic adjustments will not precisely balance spending with fund availability. A third step recalculates the relationship of budgetary demand and supply and allocates any remaining difference to changes in per-student expenditures.

5.3.4.3 Other Important Education Variables

Modeling of the primary level differs from secondary and tertiary levels because of its simultaneous calculation of net and gross enrollments and the need to assure that numbers of over-age students, many of whom are returning after earlier dropout, are consistent with the population of children who do not proceed through primary education while of appropriate grade age. Drawing on the population model's accounting of children by age, IFs includes a tracking system of the potential pool of over-age students (at least those below some reasonable cut-off age, such as 15 years) and the portion of that pool that enters into, or returns to, primary education. As rates of net enrollment and survival through primary education approach 100%, the potential pool for gross enrollment additions approaches zero.

Once students age past the various education levels and become adults, they carry their education attainment in a variety of stock variables that age with them. For instance, the internal variable *EdPriPopPer* carries the percentage of each 5-year cohort with completed primary education, and similar variables track secondary and tertiary education attainment by cohort. From these it is possible to compute the percentages of the total population with completed education at each level (e.g., *EDPRIPER*). And from the five-year cohort rates of completion and an estimate, based on dropout rates, of education years attained at each level for those who do not complete a degree, it is possible to compute the average years of formal education attainment by sex of adults of >15 years of age (*EDYRSAG15*) and >25 years of age (*EDYRSAG25*); these become key driving variables in many parts of the larger IFs system. IFs also calculates attainment between 15 and 24 years of age and between 20 and 29 (young adults).

Initializing the adult attainment levels is complicated. For instance, it requires the average years of formal education once attained by females now aged 55–59 years; that is scarce information even in high-income countries, much less in low-income ones. The data site of Barro and Lee (http://www.barrolee.com/; see Barro and Lee, 2013 for discussion) contains data from 1950 through 2010 on the percentage of adults in total who have completed each level of education. In the first year of the model's run an algorithm spreads those rates across all 5-year cohorts (older adults have less frequently completed the various levels). Barro and Lee now also provide attainment data by cohort and it might be desirable to switch over to these for countries where available.

The Barro and Lee website not only contains their estimates of average adult attainment from 1950 through 2010, but also their projections from 2015 to 2040.[41] The projections are, however, only for adults aged 15–65 years (or 25–65 years) in contrast to the historical data, which are for adults aged 15 or 25 years and older. The IFs project has used the projection values to estimate a 2015 value for attainment of education by all adults aged 15 or 25 years and older, which the model uses to initialize the adult attainment variables in its base year. In future years the model uses changes in the internal variables for completion by age of various education levels (again like *EdPriPopPer*) to update calculations of total adult attainment. Further, IFs computes a literacy rate (*LIT*), using the assumption that it is tied to adults' completion of primary education.

In addition, the education model feeds directly into creation of a number of knowledge system indices, most of which include education attainment variables such as literacy and adult attainment years, as well as variables such as expenditure on research and development and societal access to information and communications technology.

An important newer set of specifications in the IFs education model represents quality of education. Initialized with data from multiple international standardized tests (and attentive also to a data set underlying Altinok et al., 2018), model values at primary, secondary, and tertiary levels respond distally to GDP per capita at PPP and adults' years of education attainment. More proximately, quality responds to education spending per student, corruption, and sociopolitical stability relative to expected levels. In similar fashion to years of adult education attainment, the model tracks levels of education quality across the adult population, advancing it with aging. Also, like quantity of adult education, education quality affects multifactor productivity in the economic model (see Section 6.1.4.1).

5.3.4.4 Limitations

The IFs system would potentially benefit from a data-based initialization of education attainment by age in place of our algorithmic spread of total attainment, potentially drawing on data from Barro and Lee or the WIC/IIASA project to build that spread from a wide variety of data sources. This would be especially important if IFs were to move to also represent the

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[41] See http://barrolee.com/data/oup_download_c.htm for projections.

impact of age-sex specific education on age-sex specific fertility and mortality rather than driving fertility and mortality with aggregate adult attainment.

Another missing model piece is representation of pre-primary education, recognized as important also in the Sustainable Development Goals (SDGs). Further, the current representation of vocational education is very spare.

Looking forward, an increasingly egregious failure of all demographic-education modeling may be in not somehow representing (1) learning or nonformal education of adults no longer in school and (2) possible obsolescence of earlier learning. Given that countries clearly vary in nonformal education opportunities (e.g., Germany's apprenticeship program is especially strong) and that the Internet increasingly makes lifelong learning easier, future modeling may need to include some representation of nonformal education as a major supplement to formal education.

5.3.5 Comparative Scenarios

Fig. 5.18 compares the IFs Base Case scenario of education attainment of those 25 years and older globally with the revised SSP2 demographic scenario of WIC/IIASA (Section 5.1.3 noted that an original set of demographic and education projections for all five SSPs was followed in 2018 with production of a revised set focused on three of them with a base year update from 2010 to 2015). Because the WIC/IIASA system uses different data sources to initialize the variable, the initial conditions are somewhat different. The patterns of growth are, however, generally similar. Both projects suggest an increment of about 5 years in adults' average years of education over the current century. This contrasts with Barro and Lee (2015) data for the last century, which suggested a global increase of nearly eight years for that period; the anticipated slowing rate of advance reflects an increasingly well-educated global

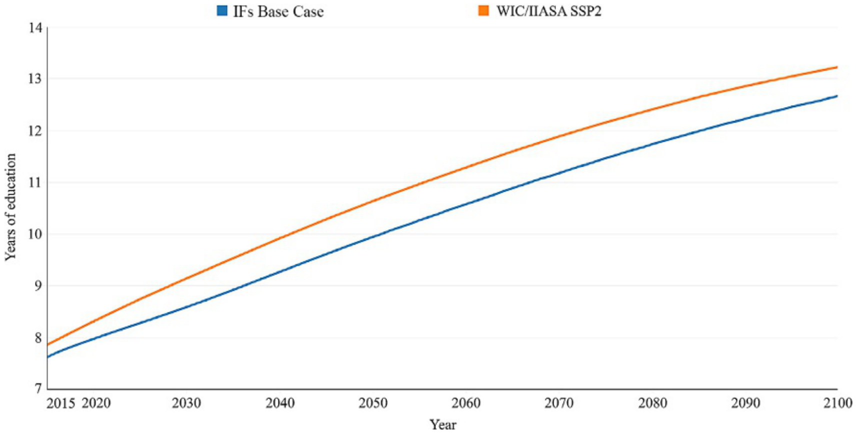

FIG. 5.18 **Global years of education of adults aged 25 years and older: Comparative scenarios to 2100.** *Note: Uses middle variant scenarios. See KC et al., 2018 for description of revised SSP2 demographic scenario. Base year differences reflect WIC/IIASA's own historical database. Source: IFs Version 7.36; historical data from Barro and Lee at http://www.barrolee.com, and comparative projection from WIC/IIASA revised SSP2 projection (values courtesy of Anne Goujon and WIC/IIASA, see Lutz et al., 2018).*

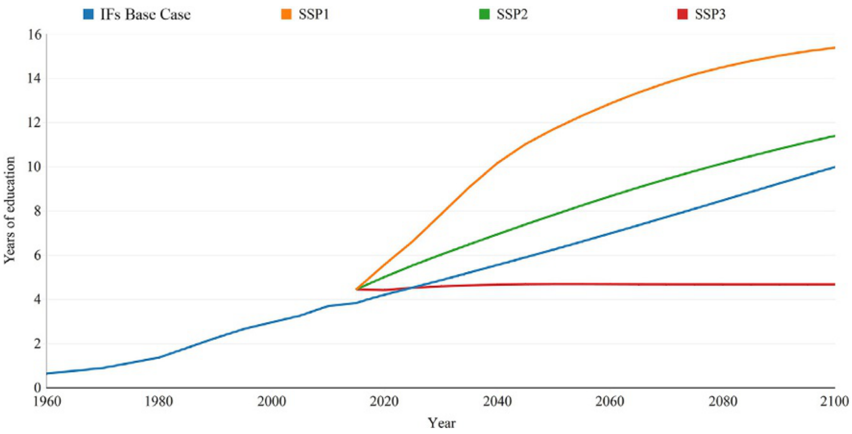

FIG. 5.19 **Years of education of adults aged 25 years and older in low-income countries: Comparative scenarios to 2100 with history from 1960.**
Note: Uses World Bank low-income group, and compares the IFs Base Case with the revised WIC/IIASA Shared Socioeconomic Pathway (SSP) scenarios (see KC et al., 2018 for SSP demographic scenario descriptions). Source: IFs Version 7.36, historical data from Barro and Lee at http://www.barrolee.com/; comparative scenarios from SSP projection revision by WIC/IIASA (values courtesy of Anne Goujon and WIC/IIASA, see Lutz et al., 2018).

population and some saturation in the potential for formal education.[42] Even with that slowing, by 2100 the average adult could have more than the equivalent of completed secondary education.

Fig. 5.19 shows the IFs Base Case and three highly divergent Shared Socioeconomic Pathway scenarios for the World Bank's low-income country grouping (see SSP discussion in Section 3.3.2.1). The lack of advance in the education attainment of adults in SSP3 (Regional Rivalry) is essentially impossible because younger adults in those countries have considerably more education than older ones; hence with the death of older adults, the average will inevitably rise.

In combination, the SSP scenarios constitute a form of extreme framing rather than equally plausible stories of the future. The IFs Base Case and SSP2 ("Middle of the Road," or the SSP equivalent of a Base Case) are arguably the most likely scenarios. They produce quite similar results, in spite of considerable methodological differences, and suggest that education attainment of adults in low-income countries will rise about six years by 2100.

5.4 HUMAN DEVELOPMENT IN SUMMARY

As a summary measure of overall human development in societies, the Human Development Index (HDI)[43] created by the United Nations Development Programme (UNDP) began

[42] Barro and Lee projections at www.barrolee.com suggest a global addition between 2015 and 2040 of 2.1 years of attainment by those between 15 and 64 years of age; this compares in that period with the IFs Base Case rise of 1.6 years for all adults aged 15 years and older.

[43] See http://hdr.undp.org/en/content/human-development-index-hdi.

as a simple average of three subindices for life expectancy, education, and GDP per capita using PPP (logged across a range to a maximum of $40,000). The Human Development Report Office of the UNDP has changed its aggregation of subindices in the HDI (explained in each *Human Development Report*) to a geometric mean of them, thereby giving more equal weight to movement across the range of each. It further changed the education subindex to a geometric mean of two subcomponents—expected years of schooling of school entrants and mean years of schooling of adults (capped at 18)—thus drawing from both flow and stock variables. Logged gross national income (GNI) per capita at PPP replaced GDP per capita, and ranges from a minimum of $100 to a maximum of $75,000. The index continues to use life expectancy.

This chapter has discussed IFs computation of two of the HDI subindices (life expectancy and education), and the next chapter will include discussion of the standard of living measure (although IFs uses GDP per capita instead of GNI per capita in its replication of the HDI).

I am aware of no other source of HDI scenarios against which to compare those from the IFs Base Case. Instead, Fig. 5.20 shows values from IFs across the four scenarios developed for the United Nations Environment Programme's Global Environmental Outlook-4 (see Section 9.2.2). The figure focuses on low-income countries, where the need and opportunity for advance in human development is greatest.

All global scenarios suggest significant, albeit saturating, growth in HDI; as indicated earlier, some of that is all but certain because of ongoing catch-up by developing countries with high-income countries on all index components. Using representation of the SSP scenarios in IFs (not shown), the global range at the end of the century is wider, from nearly flat SSPs 3 and 4 to SSPs 1 and 5 that exceed the current upper end value of 1.0 (possible because that value is scaled by current best global performance).

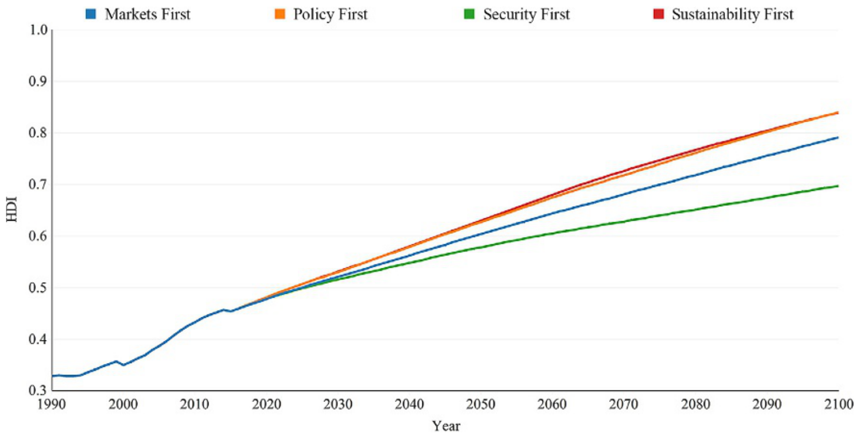

FIG. 5.20 **Human Development Index (HDI) in low-income countries: IFs implementation of GEO-4 scenarios to 2100, with history from 1990.**

Note: IFs HDI approach is based on the United Nations Development Programme's 2010 reformulated HDI methodology. See UNEP 2007 for GEO-4 scenario information. Source: IFs Version 7.36, using historical data from the 2015 UNDP Human Development Report, and comparative GEO-4 scenarios as implemented in IFs for UNEP 2007. IFs HDI projections initialized with data for each of the variables in the HDI from different sources: life expectancy from the United Nations Population Division (UNPD 2017 Revision); education from the UNESCO Institute of Statistics and Barro and Lee at http://www.barrolee.com/; and GDP per capita from the World Bank's World Development Indicators.

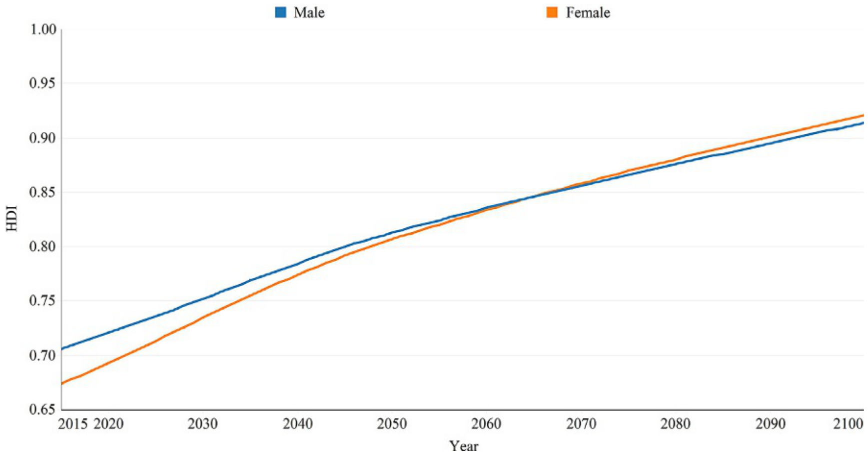

FIG. 5.21 **The global Human Development Index (HDI) by sex: IFs Base Case scenario to 2100.** *Note: IFs HDI approach is based on the United Nations Development Programme's 2010 reformulated HDI methodology. Source: IFs Version 7.36, initialized with data for each of the variables in the HDI from different sources: life expectancy from the United Nations Population Division (UNPD 2017 Revision); education from the UNESCO Institute of Statistics and Barro and Lee at http://www.barrolee.com/; and GDP per capita from the World Bank's World Development Indicators.*

Going still one step further, I am also aware of no other source of sex-differentiated HDI forecasts against which to compare those from IFs. Fig. 5.21 shows values at the global level in the IFs Base Case scenario. We see increasing saturation for both sexes as countries converge globally on the component measures and progress arguably becomes more difficult at the leading edge of the indicators in the index. In addition, we see not only the expected narrowing of differences between men and women, but the movement of women ahead of men. In fact, women already live 4 years longer globally (5 years in high-income countries and three in low-income ones). In the IFs Base Case, the global education attainment of adult females will pass that of males during this century (within a decade in high-income countries). Relative progress for women on incomes is less certain, but the use by the HDI of a cap on contribution from income makes convergence there also increasingly likely. Qualitatively, we might very reasonably question whether the condition of women in the family, economy, or governance will catch that of men, even across the entire century. Nonetheless, some progress in the relative condition of women appears highly probable.

5.5 CONCLUSION

Human development presumably involves more than improvements in health, advance in education, and increase in income. Positive connections with others and actualization of one's potential are obviously also among its elements. Although our doing so is by no means assured, health and education provide foundations on which much more can be built, and we need to turn to what some of those additional elements might be. Chapter 6 moves us into the social components of development.

References

Abel, G.J., Sander, N., 2014. Quantifying global international migration flows. Science 343 (6178), 1520–1522. https://dx.doi.org/10.1126/science.1248676.

Altinok, N., Angrist, N., Patrinos, H.A., 2018. Global Data Set on Education Quality (1965–2015). WB Policy Research Working Paper No. 8314. World Bank, Washington, DC. http://documents.worldbank.org/curated/en/706141516721172989/pdf/WPS8314.pdf.

Angeles, L., 2010. Demographic transitions: analyzing the effects of mortality on fertility. J. Popul. Econ. 23 (1), 99–120. https://dx.doi.org/10.1007/s00148-009-0255-6.

Barakat, B.F., Durham, R.E., 2014. Future education trends. In: Lutz, W., Butz, W.P., Samir, K.C. (Eds.), World Population and Human Capital in the Twenty-First Century. Oxford University Press, Oxford, UK, pp. 397–433.

Barro, R.J., Lee, J.-W., 2013. A new data set of educational attainment in the world, 1950–2010. J. Dev. Econ. 104 (September), 184–198. https://dx.doi.org/10.1016/j.jdeveco.2012.10.001.

Barro, R.J., Lee, J.-W., 2015. Education Matters: Global Schooling Gains from the 19th to the 21st Century. Oxford University Press, New York, NY.

Blössner, M., de Onis, M., 2005. Malnutrition: Quantifying the Health Impact at National and Local Levels. Environmental Burden of Disease Series, No. 12. World Health Organization, Geneva, Switzerland.

Bruns, B., Mingat, A., Rakotomalala, R., 2003. Achieving Universal Primary Education by 2015: A Chance for Every Child. World Bank, Washington, DC.

Cuaresma, J.C., Lutz, W., 2007. Human Capital, Age Structure and Economic Growth: Evidence From a New Dataset. Interim Report IR-07-011. International Institute for Applied Systems Analysis, Laxenburg, Austria. http://pure.iiasa.ac.at/8444/1/IR-07-011.pdf.

Delamonica, E., Mehrotra, S., Vandemoortele, J., 2001. Is EFA Affordable? Estimating the Global Minimum Cost of 'Education for All'. Innocenti Working Paper No. 87. UNICEF Innocenti Research Centre, Florence, Italy.http://ideas.repec.org/p/wpa/wuwpdc/0403007.html.

Dodman, D., 2009. Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. Environ. Urban. 21 (1), 185–201. https://dx.doi.org/10.1177/0956247809103016.

Ezzati, M., Lopez, A.D., Rodgers, A., Murray, C.J.L. (Eds.), 2004a. Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors. World Health Organization, Geneva, Switzerland.

Ezzati, M., Vander Hoorn, S., Rogers, A., Lopez, A.D., Mathers, C.D., Murray, C.J.L., 2004b. Potential health gains from reducing multiple risk factors. In: Ezzati, M., Lopez, A.D., Rodgers, A., Murray, C.J.L. (Eds.), Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors. Vol. II.World Health Organization, Geneva, Switzerland, pp. 2167–2190.

Fuchs, R., Goujon, A., 2014. Future fertility in high fertility countries. In: Lutz, W., Butz, W.P., Samir, K.C. (Eds.), World Population and Human Capita in the Twenty-First Century. Oxford University Press, Oxford, UK, pp. 147–225.

Global Burden of Disease (GBD) Health Financing Collaborator Network, 2017a. Evolution and patterns of global health financing 1995-2014: development assistance for health, and government, prepaid, private, and out-of-pocket health spending in 184 countries. Lancet 389 (10083), 1981–2004. https://dx.doi.org/10.1016/S0140-6736(17)30874-7.

Global Burden of Disease (GBD) Health Financing Collaborator Network, 2017b. Future and potential spending on health 2015-2040: development assistance for health, and government, prepaid, private, and out-of-pocket health spending in 184 countries. Lancet 389 (10083), 2005–2030. https://dx.doi.org/10.1016/S0140-6736(17)30873-5.

Global Burden of Disease (GBD) Mortality and Causes of Death Collaborators, 2016. Global, regional, and national life expectancy, all-cause mortality, and cause-specific mortality for 249 causes of death, 1980-2015: a systematic analysis for the global burden of disease study 2015. Lancet 388 (10053), 1459–1544. https://dx.doi.org/10.1016/S0140-6736(16)31012-1.

Goujon, A., KC, S., Speringer, M., Barakat, B., Potancokov, M., Eder, J.A., et al., 2016. A harmonized dataset on global educational attainment between 1970 and 2060—an analytical window into recent trends and future prospects in human capital development. J. Demograph. Econ. 82 (3), 315–363. https://dx.doi.org/10.1017/dem.2016.10.

Hilderink, H., Lucas, P., 2008. Towards a Global Integrated Sustainability Model: GISMO 1.0 Status Report. PBL Report 550025002. PBL Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands. http://www.pbl.nl/sites/default/files/cms/publicaties/550025002.pdf.

Hughes, B.B., 2004. The Base Case of International Futures (IFs): Comparison with Other Forecasts. Working Paper 2004.04.17 prepared for the National Intelligence Council Project 2020, Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/2004.04.17_IFs_Base_Case_Comparisons_to_Other_Forecasts_v46_0.pdf.

Hughes, B.B., Kuhn, R., Peterson, C.M., Rothman, D.S., Solórzano, J.R., 2011a. Improving Global Health. Vol. 3 of the Patterns of Potential Human Progress Series. Paradigm Publishers and Oxford University Press, Boulder, CO; New Delhi, India.

Hughes, B.B., Kuhn, R., Peterson, C.M., Rothman, D.S., Solórzano, J.R., Mathers, C.D., Dickson, J.R., 2011b. Projections of global health outcomes from 2005 to 2060 using the international futures integrated forecasting tool. Bull. World Health Organ. 89 (7), 478–486. https://dx.doi.org/10.2471/BLT.10.083766.

Hughes, B.B., Kuhn, R., Margolese-Malin, E.S., Rothman, D.S., Solorzano, J.R., 2014. Opportunities and Challenges of a World with Negligible Senescence. Final Project Report to the SENS Research Foundation. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/Hughes_2014_SENS.pdf.

Hughes, B.B., Kuhn, R., Margolese-Malin, E.S., Rothman, D.S., Solórzano, J.R., 2015. Opportunities and challenges of a world with negligible senescence. Technol. Forecast. Soc. Chang. 99 (October), 77–91. https://dx.doi.org/10.1016/j.techfore.2015.06.031.

Ignaciuk, A.M., Peterson, S., Hubler, M., Dellink, R.B., Lucas, P.L., Hilderink, H.B.M., 2009. An Economy Model for GISMO—DART-PBL Technical Documentation. PBL Publication No. 550025003. PBL Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands. https://www.ifw-members.ifw-kiel.de/publications/dart-pbl-the-core-version-technical-documentation/dart-pbl-technical-documentation.

Irfan, M.T., 2008. A global education transition: computer simulation of alternative paths in universal basic education. (PhD dissertation). Josef Korbel School of International Studies, University of Denver, Denver, CO. http://www.ifs.du.edu/documents/reports.aspx

KC, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Chang. 42 (January), 181–192. https://dx.doi.org/10.1016/j.gloenvcha.2014.06.004.

KC, S., Barakat, B., Goujon, A., Skirbekk, V., Sanderson, W., Lutz, W., 2010. Projection of populations by level of educational attainment, age and sex for 120 countries for 2005-2050. Demogr. Res. 22 (15), 383–472. https://dx.doi.org/10.4054/DemRes.2010.22.15.

KC, S., Potančoková, M., Bauer, R., Goujon, A., Striessnig, E., 2013. Summary of Data, Assumptions and Methods for New Wittgenstein Centre for Demography and Global Human Capital (WIC) Population Projections by Age, Sex and Level of Education for 195 Countries to 2100. Interim Report IR-13-018. International Institute for Applied Systems Analysis, Laxenburg, Austria. http://pure.iiasa.ac.at/10742/1/IR-13-018.pdf.

KC, S., Lutz, W., Potančoková, M., Abel, G., Barakat, B., Eder, J., et al., 2018. Approach, methods, and assumptions. In: Lutz, W., Goujon, A., KC, S., Stonawski, M., Stilianakis, N. (Eds.), Demographic and Human Capital Scenarios for the 21st Century. Publications Office of the European Union, Luxembourg, pp. 19–28.

Klanjscek, T., Caswell, H., Neubert, M.G., Nisbet, R.M., 2006. Integrating dynamic energy budgets into matrix population models. Ecol. Model. 196 (3), 407–420. https://dx.doi.org/10.1016/j.ecolmodel.2006.02.023.

Kontis, V., Bennett, J.E., Mathers, C.D., Li, G., Foreman, K., Ezzati, M., 2017. Future life expectancy in 35 industrialized countries: projections with a Bayesian model ensemble. Lancet 389 (10076), 1323–1335. https://dx.doi.org/10.1016/S0140-6736(16)32381-9.

Kuhn, R., Rothman, D.S., Turner, S., Solórzano, J., Hughes, B., 2016. Beyond attributable burden: estimating the avoidable burden of disease associated with household air pollution. PLoS ONE. 11(3)e0149669. https://dx.doi.org/10.1371/journal.pone.0149669.

Lee, J.-W., Lee, H., 2016. Human capital in the long run. Dev. Econ. 122, 147–169. https://dx.doi.org/10.1016/j.jdeveco.2016.05.006.

Lutz, W., Goujon, A., 2001. The world's changing human capital stock: multi-state population projections by educational attainment. Popul. Dev. Rev. 27 (2), 323–339. http:/www.jstor.org/stable/2695213.

Lutz, W., KC, S., 2013. Demography and Human Development: Education and Population Projections. UNDP Occasional Paper 2013/04. Human Development Report Office, United Nations Development Programme, New York, NY. http://www.hdr.undp.org/sites/default/files/hdro_1304_lutz_kc.pdf.

Lutz, W., KC, S., 2014. The rise of global human capital and the end of world population growth. In: Lutz, W., Butz, W.P. (Eds.), World Population and Human Capital in the Twenty-First Century. Oxford University Press, Oxford, UK, pp. 519–562.

Lutz, W., KC, S., 2018. Alternative scenarios for future world population growth. In: Lutz, W., Goujon, A., KC, S., Stonawski, M., Stilianakis, N. (Eds.), Demographic and Human Capital Scenarios for the 21st Century. Publications Office of the European Union, Luxembourg, pp. 115–121.

Lutz, W., Skirbekk, V., 2014. How education drives demography and knowledge informs projections. In: Lutz, W., Butz, W.P., Samir, K.C. (Eds.), World Population and Human Capital in the Twenty-First Century. Oxford University Press, Oxford, UK, pp. 14–38.

Lutz, W., Sanderson, W., Scherbov, S., Wolfgang, L., 1996. Probabilistic population projections based on expert opinion. In: Lutz, W., Butz, W.P., KC, S. (Eds.), The Future Population of the World: What Can We Assume Today. Earthscan, London, UK, pp. 397–428.

Lutz, W., Goujon, A., Wils, A., 2005. Forecasting Human Capital: Using Demographic Multi-State Methods by Age, Sex, and Education to Show the Long-Term Effects of Investments in Education, WP-07-03. Education Policy and Data Center, Washington, DC. http://www.epdc.org/sites/default/files/documents/Forecasting%20Human%20Capital.pdf.

Lutz, W., Goujon, A., KC, S., Sanderson, W., 2007. Reconstruction of populations by age, sex and level of educational attainment for 120 countries for 1970–2000. In: Lutz, W. (Ed.), Vienna Yearbook of Population Research 2007. Austrian Academy of Sciences, Vienna, Austria, pp. 193–235. https://doi.org/10.1553/populationyearbook2007s193.

Lutz, W., Butz, W.P., Samir, K.C. (Eds.), 2014. World Population and Human Capital in the Twenty-First Century. Oxford University Press, Oxford, UK.

Lutz, W., Goujon, A., KC, S., Stonawski, M., Stilianakis, N., 2018. Demographic and Human Capital Scenarios for the 21st Century. Publications Office of the European Union, Luxembourg.

Maddison, A., 2007. Contours of the World Economy, 1–2030 AD. Oxford University Press, New York, NY.

Mathers, C.D., Loncar, D., 2005. Updated Projections of Global Mortality and Burden of Disease, 2002–2030: Data Sources, Methods and Results. Evidence and Information for Policy Working Paper, World Health Organization, Geneva, Switzerland. https://www.who.int/healthinfo/statistics/bodprojectionspaper.pdf.

Mathers, C.D., Loncar, D., 2006a. Projections of global mortality and burden of disease from 2002 to 2030. PLoS Med. 3 (11)e442. https://dx.doi.org/10.1371/journal.pmed.0030442.

Mathers, C.D., Loncar, D., 2006b. Protocol S1. Technical Appendix to Mathers and Loncar 2006a. https://dx.doi.org/10.1371/journal.pmed.0030442.sd004.

McEvedy, C., Jones, R., 1978. Atlas of World Population History. Penguin Books, Middlesex, UK.

McMahon, W.W., 1999. Education and Development: Measuring the Social Benefits. Oxford University Press, New York, NY.

Moyer, J.D., Bohl, D., Petry, C., Scott, A., Solórzano, J.R., Kuhn, R., 2018. Persistent, Pernicious, and Preventable: Forecasting the Global Burden of Severe Acute Malnutrition. (Manuscript submitted for publication).

Murray, C.J.L., Lopez, A.D., 1996. The Global Burden of Disease: A Comprehensive Assessment of Mortality and Disability from Diseases, Injuries, and Risk Factors in 1990 and Projected to 2020. Harvard University Press, Cambridge, MA.

Nussbaum, M., 2011. Creating Capabilities: The Human Development Approach. Harvard University Press, Cambridge, MA.

O'Neill, B.C., Dalton, M., Fuchs, R., Jiang, L., Pachauri, S., Zigova, K., 2010. Global demographic trends and future carbon emissions. Proc. Natl. Acad. Sci. U. S. A. 107 (31), 17521–17526. https://dx.doi.org/10.1073/pnas.1004581107.

Omran, A.R., 1971. The epidemiologic transition: a theory of the epidemiology of population change. Milbank Mem. Fund Q. 49 (4), 509–538. http://www.jstor.org/stable/3349375.

Rogers, A., 1975. Introduction to Multiregional Mathematical Demography. John Wiley & Sons, New York, NY.

Sen, A., 1999. Development as Freedom. Oxford University Press, New York, NY.

United Nations Department of Economic and Social Affairs (UNDESA), 1956. Manual III: Methods for Population Projections by Age and Sex. United Nations, New York, NY. https://ec.europa.eu/eurostat/ramon/statmanuals/files/UNSD_manual3_population_estimates_1956_EN.pdf.

United Nations Population Division (UNPD), 2015. World Population Prospects: The 2015 Revision, Methodology of the United Nations Population Estimates and Projections. Working Paper No. ESA/P/WP.242. United Nations Department of Economic and Social Affairs, New York. https://esa.un.org/unpd/wpp/publications/Files/WPP2015_Methodology.pdf.

United Nations Population Division (UNPD), 2017. World Population Prospects: The 2017 Revision: Key Findings and Advance Tables. Working Paper No. ESA/P/WP.248, United Nations Department of Economic and Social Affairs, New York. https://esa.un.org/unpd/wpp/Publications/Files/WPP2017_KeyFindings.pdf.

Vallin, J., Meslé, F., 2010. Will life expectancy increase indefinitely by three months every year? Popul. Soc. 473 (December), 1–4. https://www.ined.fr/fichier/s_rubrique/19141/population.societies.2010.473.life.expectancy.increase.en.pdf.

Wils, A., 2007. Window on the Future: 2025—Projections of Education Attainment and Its Impact. Education Policy and Data Center, Washington, DC. https://www.foresightfordevelopment.org/sobipro/55/576-window-on-the-future-2025-projections-of-education-attainment-and-its-impact.

Wils, A., O'Connor, R., 2003. The Causes and Dynamics of the Global Education Transition. AED Working Paper, Academy for Educational Development, Washington, DC.

CHAPTER

6

The Future of Socioeconomic Development

We humans have no future without membership in society, minimally in kinship groupings that support the bearing and raising of children. Wellbeing much beyond mere existence and reproduction benefits greatly from larger and more complex societies with extended patterns of production and exchange (economies) and organization (governance). This chapter moves to a discussion of how modelers think about the future of these social aspects of development, beginning with economics.

6.1 ECONOMICS

It is easy to develop scenarios of economic growth simply using past patterns. The long-term moving average of global annual economic growth has stayed in the range of 2.5–3.5% since the mid-1970s, making rates in that range a reasonable guess for growth going forward. Such simple projection, analogously for countries, would be useful for many purposes.

More elaborate economic models can help in a number of ways, however, especially distinguishing across temporal circumstances and countries. Temporally, global economic growth may slow because of cessation of population growth and convergence of developing economies with higher-income ones that have lower growth rates. At the country level, a more elaborated economic model, especially one connected to models of other issue areas, provides many leverage points for "what-if" policy analysis that could accelerate or retard more localized growth.

6.1.1 Concepts, Structures, and Data

In demographics, the central accounting system that organizes thinking about change over time is one of stocks, namely population by age and sex. The key dynamic formulations focus on flows—births, deaths, and migration—that change those stocks. In economic analysis, in

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distinction, the most widely used accounting systems organize thinking about flows, namely the national accounting systems that portray annual production, exchange, and consumption.

Why the seeming reversal of central focus of accounting in economics relative to demographics? It is because people and their wellbeing are the central focus of thinking about the future and people do not, so to speak, directly eat or otherwise consume capital and labor stocks but rather the annual production of those. This heavy focus on flows has many implications for socioeconomic thinking and forecasting, including the relatively lesser statistical attention that has been given to economic stocks of wealth (whether that of households or firms) than to the flow of income, as in gross national product (GNP) or gross domestic product (GDP).

Consider, for instance, our great attention to recessions and to avoiding them. Japan has very frequently been in recession since the early 1990s (GDP grew by only about 20% in total in the 25 years from 1990 through 2015) and is perceived to have lost economic ground. Yet the contributions to building of Japanese capital stock and therefore wealth (including housing, factories, and infrastructure) every year even from a stabilizing GDP more than offset depreciation of capital created 30–40 years earlier when the economy was much smaller. That is, Japan's wealth has been continuing to grow quite significantly; not a headline we tend to see.[1] And given that population started to decline after 2010, both per capita GDP and wealth could continue to grow for many years.

Similarly, the focus on distribution within societies is almost always on income. An illustrative exception is Piketty's (2014) focus on capital, not only in giving his book that title but also in his dataset drawn from information on estates. Yet, Piketty's empirical focus on capital was mostly historical, not on efforts to forecast it, despite his admonitions about future problems related to its growing concentration.[2] Still further, our attention to economic flows sometimes diverts attention from the natural resource stocks that can be run down in the process of enhancing income flows. These include fresh water in aquifers as well as forests and mineral stocks.

Important dynamic formulations in economics attempt to deal with these issues through attention to the interaction of flows and stocks, such as (1) investment and its increase of capital, (2) voluntary or involuntary entrance into, departure from, or absence of workers from the labor force (like capital, labor force is a stock), and (3) the rate of change in productivity of that capital and labor (total productivity again being a stock). The next sections look in turn at the static accounting of flows (that is, portraits of the economy at single points in time) and the dynamic interaction of stocks and flows across time.

6.1.1.1 Flow-Based Accounting

Although accounting for economic flows has roots at least back to Francois Quesnay's Tableau économique in 1758 and Léon Walras's work on general equilibrium theory in 1874, it

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[1] Data from analysis of the Credit Suisse Global Wealth Report 2014 at https://publications.credit-suisse.com/tasks/render/file/?fileID=60931FDE-A2D2-F568-B041B58C5EA591A4 (provided to the IFs project courtesy of Anthony Shorrocks) suggest that total nominal Japanese wealth grew by about 20 percent in just four years between 2010 and 2014; inflation was extremely low, so real wealth growth was strong.

[2] Does one ever see forecasts of per capita wealth through 2030 or 2050? A web search for those will generally pull up materials that inaccurately use GDP as a measure of wealth.

was Wassily Leontief who pushed forward its concepts and measurement—and ultimately its modeling—in Nobel prize–winning work in the middle of the 20th century (Leontief, 1951). The input-output matrix that his work produced represents the flow of materials and services across economic sectors in the production process. Leontief's representation also included the flow of sectoral output not just to other sectors but also to final demand—the sum of final demand net of imports being one calculation of GDP. Extensions have added exports as an additional target of production, imports as an additional input to sectoral production, and rows that represent the value added that labor and capital inputs provide to production (as measured by wages and operating surplus of firms net of depreciation and taxes minus subsidies); the sum of value added is the second approach to calculation of GDP. See Table 6.1 for an illustration of an input-output matrix as extended with final demand and value added from capital and labor inputs.

Yet even the representation in Table 6.1 inadequately describes the flows that shape an economy. Further extensions begin to more comprehensively represent economic agents—namely households, firms, and governments—and the flows among them. For instance, households use labor income and transfers from the government to finance consumption, and governments account for revenues from households and firms in determining their expenditure capability, including flows back to them. To capture these flows, it is necessary to go beyond the representation of Table 6.1 to the portrayal of Fig. 6.1 and the tabular elaboration of such an extended system in what we call a social accounting matrix (SAM).

The United Nations has worked to create a common statistical foundation for SAMs via its System of National Accounts (SNA), most recently revised in 2008. Further, the Global Trade and Analysis Project (GTAP), a worldwide consortium of scholars and institutions led by the

TABLE 6.1 Extended Input-Output Model, Hypothetical Example

	Intersectoral Flows			**Final Demand**				
	Primary	**Industrial**	**Services**	**Household Consumption**	**Government Consumption**	**Capital Formation**	**Exports**	**Total**
Primary	27	130	10	12	50	32	100	361
Industrial	25	400	250	123	45	212	312	1367
Services	40	647	770	345	216	67	189	2274
Imports	57	89	129					275
Labor value added	112	65	640					817
Capital value added	100	36	475					611
Total	361	1367	2274	480	311	311	601	5705

Note: Columns are users of goods and services (providers of currency), rows are suppliers of goods and services. Primary includes agriculture and energy. See Horowitz and Planting (2006, pp. 2–11), and Wixted, Yamano, and Webb (2006, p. 9) for further elaboration of input-output model concepts.
Source: Author.

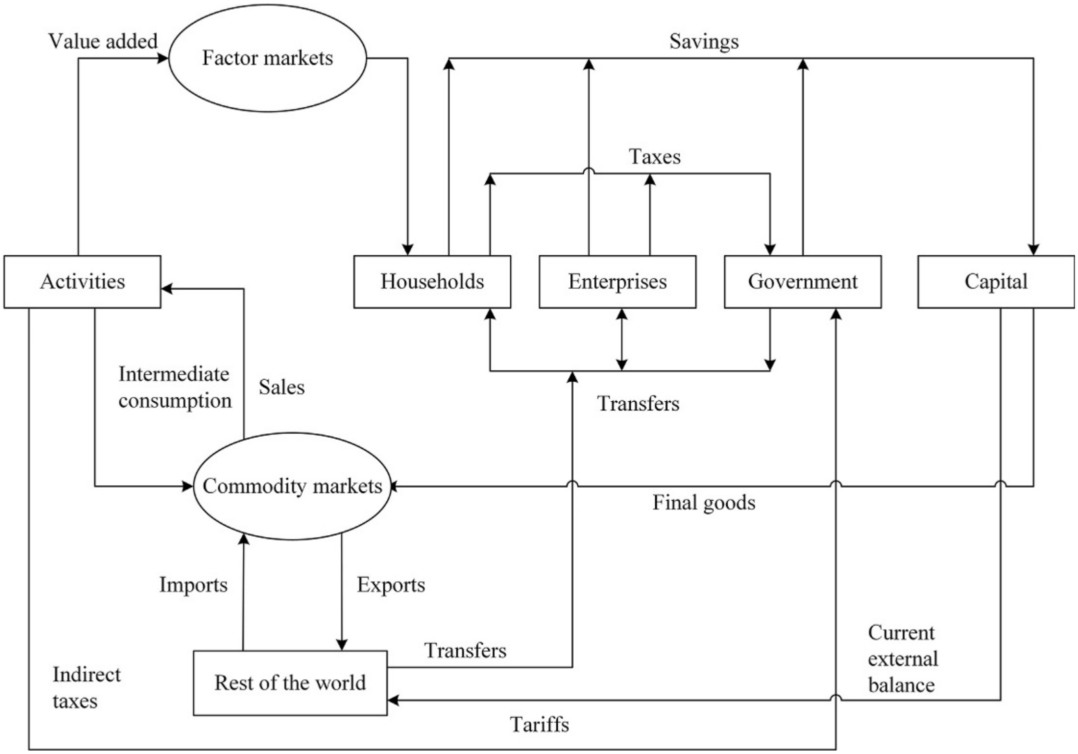

FIG. 6.1 Flows represented in a social accounting matrix.
Source: Adapted by author from Chung-I Li, J. 2002. A 1998 Social Accounting Matrix (SAM) for Thailand. TMD Discussion Paper 95, Figure 1. International Food Policy Research Institute, Washington, DC; Adapted and reproduced with permission from the International Food Policy Research Institute, www.ifpri.org. The original paper in which this figure appears is available online at http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/63061.

Center for Global Trade Analysis at Purdue University, has assembled an extensive database of input-output matrices and associated SAM information (Aguiar et al., 2016).[3] Yet national accounting systems lag well behind the SNA recommendations, and the GTAP data, while strong, constantly improved, and widely used (including in the IFs project), have incomplete coverage of countries and desired SAM elements.

Despite these limitations, the use of a SAM is critical to most economic policy analysis and forecasting for two reasons. First, it allows connection of the economy to other human systems. In the case of IFs, it allows the connection of government finance to the education and health models discussed in Chapter 5, and it facilitates connection of the physical representations of agriculture, energy, and infrastructure (discussed in Chapter 7) to the financial value representations in the SAM. Second, and closely related, it keeps those connections

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[3] Vos (1989) and Vos and de Jong (1995) elaborated the concept of a world accounting matrix (WAM) and developed one for 1990. The GTAP database, supported also by extensions of the UN System of National Accounts, now makes it possible for global models to build and forecast WAMs. Vos's work at the United Nations tied social accounting back to Project LINK, which much earlier helped initiate world modeling.

honest by avoiding prescriptive use of financial resources (e.g., a massive expenditure program for infrastructure) without considering the source of the resources. The rows and columns of financial flows for firms, households, governments, and the outside world in the SAM must balance in each year.

6.1.1.2 Economic Growth Dynamics

The representation of both value-added production and final demand within the SAM structure is critical to the discussion of economic change. In shorter-term economic forecasting, it often makes sense to focus heavily on the demand side, as economic analysts do when considering the potential for recessions or recovery from them (heavily driven by household, firm, and government demand for goods and services). In longer-term forecasting, the swings of demand become much less important relative to the long-term trend of supply. Long-term forecasting focuses on production.

Simple techniques for forecasting production may look to a single driver. In the heavily agrarian 18th century, physiocrats identified the productive use of land as the source of wealth. More recently, and with a stronger basis across economic eras, Ayres and Warr (2009) proposed that economic growth is fundamentally tied to energy supply. Turning to multidriver models, KLEM (capital-labor-energy-materials) production functions have been in significant use since Berndt and Wood (1975) introduced them. Yet even though changes in energy and other KLEM components are well known to have an impact on production, they will be available at some price, and efficiencies of use can vary quite dramatically.

By far the most common contemporary approach to understanding production is to focus on capital, labor, and either technology or a somewhat broader concept of multifactor productivity (MFP) of that capital and labor (also referred to as total factor productivity or TFP). The Cobb–Douglas production function is the formulation most typically used to link these three stocks to current production output.

$$Y = A * K^{\alpha} L^{\beta}$$

where

Y = total production, often GDP
A = total factor productivity
a and *ß* = output elasticities of capital and labor (often *ß* = 1 - a implying constant returns to scale)

In spite of its common representation as a constant in this equation, we know that A (total factor productivity) is not a constant. Solow estimated that technical change accounted for 87.5% of growth in economic output per worker hour in the United States between 1909 and 1949 (1957, p. 320; see also 1956), and A became known as the Solow residual, a somewhat strange term for such a large factor.[4] It became standard practice to represent an exogenously specified term for growth of technology in front of the capital and labor terms as "disembodied" technological progress (Allen, 1968, Chapter 13).

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[4] Not the first to produce such an estimate, Solow (1957, p. 317) credited Fabricant (1954) with having estimated 90 percent for the 1871–1951 period.

From growth accounting estimates in four panels of countries, Barro and Sala-i-Martin (2004, pp. 439–440) reported unweighted average estimates of TFP that are considerably lower than Solow found, but still impressive: 40.7% for the G-7 countries in 1947–1973 (34% for the United States), 35% for the G-7 countries in 1960–1995 (24% for the United States), 14.4% for seven Latin American countries in 1940–1990, and 14.2% for four East Asian countries in 1966–1990. With these findings, and with the recognition that potential labor supply is relatively easily forecast from demographics (necessarily combined, of course, with forecasts of participation rates, including those of women) and that capital stock responds to investment rates that tend not to change rapidly,[5] much of the focus on understanding long-term economic growth logically shifts to understanding TFP or MFP.

Many organizations contribute to the database for analyzing economics across time, including estimating labor productivity or total factor productivity. Among them are members of the United Nations family, including the International Monetary Fund, the United Nations Industrial Development Organization, and the World Bank, whose World Development Indicators (WDI) draw on the IMF and a wide variety of other sources. For high-income countries and selected developing ones, data from the Organisation for Economic Co-operation and Development (OECD) are valuable. The Conference Board, a non-profit, business-based research organization, also makes available extensive data, as does the Penn World Table project via its depository at the University of Groningen.

6.1.2 Economic Transitions

While many standard economic data help us understand the transitions that have been occurring economically, they very often go back only to 1960. A longer perspective is very useful and fortunately, as noted in Chapter 2, Angus Maddison (2001, 2003, 2007) has given us the basis for that. His research is the source of Figs. 6.2 and 6.3.

The first of the figures provides estimates of the average long-term global GDP per capita. The per capita level was little different in 1500 than it was two millennia ago. The growth rate then began to advance in the age of discovery, and especially with the beginning of the Industrial Revolution. The rate accelerated until the second half of the 20th century, as indicated by data from Maddison[6] and the WDI for subsequent periods: 1820–1870 (world: 0.31%; England/Great Britain: 0.86%), 1870–1950 (world: 1.09%; England/Great Britain: 0.98), 1950–1980 (world: 2.57%; England/Great Britain: 2.10%), and 1980–2010 (world: 1.85%; England/Great Britain: 2.07%). It appears that the acceleration may have ended or even reversed in recent decades. If so, the total rate of global GDP growth may decline in coming decades, especially as rates of growth in population and therefore labor force growth decline through this century.

The historical GDP growth rates for the world and England also hint at the initial pulling away from the rest of the world by the earlier industrial countries like England, followed by subsequent movement toward catch-up by other countries. Fig. 6.3 reinforces that by illustrating another long-term transition pattern of great importance. It shows how 500 years ago

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[5] China's very high rate of savings and investment illustrates an exception and the importance of also giving considerable attention to those rates.

[6] The Maddison historical series are available online from the Groningen Growth and Development Centre at the University of Groningen; see http://www.ggdc.net/maddison/maddison-project/data.htm.

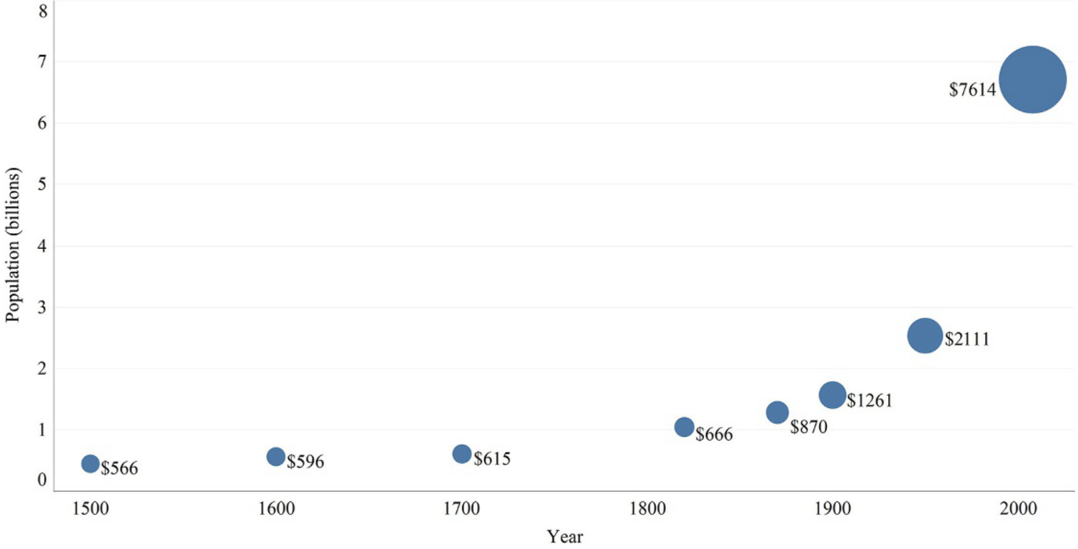

FIG. 6.2 **World GDP per capita ($2011) and global population: History since 1500.**
Note: Patterned after a figure previously available at Our World in Data (https://ourworldindata.org) through a CC BY-SA 3.0 license. Maddison data converted to $2011. Source: Author, using data from the Maddison Project (Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD, available at http://www.ggdc.net/maddison/oriindex.htm).

areas that were to become the great powers of Europe accounted for less than 20% of the global GDP, while China and India alone accounted for about 50%. Further, at that time GDP per capita (not shown) was fairly comparable for the Western European countries and China and India (as it had been 1500 years earlier). By 1960, after what economic historians refer to as the Great Divergence, China and India had fallen well below 20% of global GDP. Further, instead of relatively equal GDPs per capita around the world, that of Western Europe was more than 50 times that of China and India (not shown).

These long-term patterns reinforce our understanding of how greatly economic growth rates can vary around the world over time, and how different countries (or groups of them) can surge or fall back in growth, both diverging and converging. With respect to looking ahead, Baldwin (2016) wrote of "The Great Convergence," and the IFs Base Case scenario suggests that in 2020 the ratio of GDP per capita in Western Europe to that in China and India could fall to 7.9. Although population patterns underlie these phenomena in part, differential population and labor force growth account for a fairly small portion of the dynamic. Instead, capital growth, and the advance of productivity, account for a very large portion of economic growth. As indicated earlier, productivity is the dominant uncertainty in our economic modeling. It has great importance in the overall IFs system because of that, but more generally because it is one of the critical points where influences from many issue areas and therefore models (e.g., human capital, social capital, and physical variables) come together. Government finance, discussed later in this chapter, is a second such point of interacting influences.

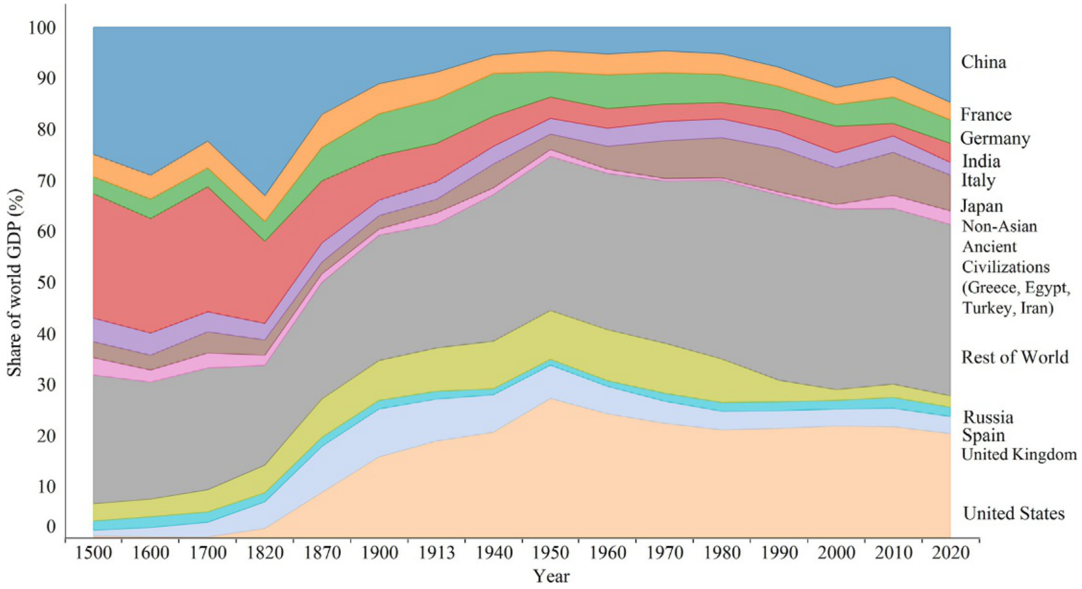

FIG. 6.3 **Global distribution of GDP: History since 1500 and forecast to 2020.**
Note: Patterned after a figure previously available at Our World in Data (https://ourworldindata.org) through a CC BY-SA 3.0 license. X-axis representation of time elaborates more recent years to portray increasing global pace of change. Source: Author, using data from the Maddison Project (Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD, available at http://www.ggdc.net/maddison/oriindex.htm), blended with data since 2008 from the World Bank's World Development Indicators and International Monetary Fund estimates through 2020.

6.1.3 Modeling Economics

The discussion thus far of economic concepts and structures focused attention on two sets: (1) those that portray supply and demand flows in balanced accounting systems and (2) those that address the dynamics of stocks and flows, with some special attention to economic productivity and growth. That same division can help us understand economic modeling, although models of special interest to this discussion attend to both in some fashion.

Comparative static and *static sequential systems* focus almost entirely on the patterns of flows that SAMs represent at particular points in time. Those models help their users explore the impacts of shocks on a system in equilibrium. What if trade becomes more or less open? What if households shift more or less money into savings? The models represent changes in equilibrating variables (such as prices or interest rates) and adaptation of agents (households, firms, and governments) so as to create a new equilibrium. Use of such models is often not very concerned with temporal dynamics, focusing instead on representing the determinants of alternative equilibria (known, of course, actually to require time to move among them). Considerable analysis with GTAP data representing SAMs falls into this category.

Models in this category are often called computable general equilibrium (CGE) and sometimes applied general equilibrium (AGE) models.[7] Full CGE models represent demand and

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[7] The CPB Netherlands Bureau for Economic Policy Analysis (1999, pp. 2–3) describes WorldScan as an Applied General Equilibrium model.

supply sides for goods and services, labor, and investment, with prices that equilibrate demand and supply of each. One purpose of CGEs is understanding distribution of income and consumption across different segments of society, as when households are differentiated by urban/rural location, skill level, economic sector, or other typology.

The global modeling and policy analysis communities are, of course, not concerned just with shorter-term economic adjustments but also with longer-term change, and especially economic growth. This concern directs our focus heavily to the production side of the equation and exploration of potential growth in stocks of production factors as a foundation for changing income and consumption levels. This second general type of economic modeling includes *macroeconomic growth models*. One example is the ENV-Growth model used by the OECD to generate GDP forecasts for the SSPs.[8] Another example is MaGE (Macroeconometrics of the Global Economy), a model of the French research center CEPII (Centre d'Etudes Prospectives et d'Informations Internationales) for forecasting economic growth of 167 countries to 2100.[9] This is not to imply that attention to demand and its equilibrium with supply is unimportant in growth models, especially those with a shorter-term focus, for which inadequate demand levels may well affect growth. But the demand side of long-term models is less likely to drive our analysis of economic growth than the supply side will. Thus many basic macroeconomic growth models do not have much sectoral or agent-category representation.

More generally, however, attention to human, social, and sustainable development issues benefits from *long-term modeling that is more hybrid* in its structure, combining the somewhat elaborated equilibrating flow accounting of a SAM with the dynamics of a growth model. While the SAM is inherently a static picture of all the economic flows across sectors and agents of the economy, the equilibrium can be changed not only in response to various exogenous shocks at a single point in time (comparative statics modeling) but also by either endogenous forces or exogenous assumptions (scenarios) that operate over time. And different equilibria (especially their savings/investment and government spending patterns) have implications for temporal dynamics. Hence much economic modeling within integrated assessment models attempts to represent both equilibration and dynamics. Attention to goal horizons like those of the SDGs, now only about a decade in the future, reinforces the utility of attention to supply and demand dynamics.

6.1.3.1 The Hybrid: Dynamic Equilibrium Models

Large numbers of global economic models sit largely outside the integrated assessment (IAM) and global modeling communities. One commercial economic model, the Oxford Economics Global Economic Model (GEM), is well known and widely used by multinational corporations and other clients. GEM represents 46 countries in detail (12 economic sectors) with "headline forecasts" for another 30 countries.[10] Forecast horizons are 5, 10, and 25 years. The company's description indicates that GEM combines a dynamic-stochastic general

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[8] See "Supplementary Note for the SSP Data Set," available at https://tntcat.iiasa.ac.at/SspDb/static/download/ssp_suplementary%20text.pdf. See also Dellink et al., 2017.

[9] For information on MaGE, see Fouré and Fontagné, 2016 and also http://www.cepii.fr/CEPII/en/bdd_modele/models.asp. The POLES system uses forecasts from MaGE and the United Nations Population Division.

[10] A description of the GEM model can be found at http://docplayer.net/1198373-April-2015-the-oxford-economics-global-economic-model.html.

equilibrium structure with statistical analysis of change across time to address the speed at which variables return to equilibrium after a shock (a hybrid approach it calls "macroeconomic error correction").

While results from GEM are widely used, the focus in this chapter moves beyond strictly economic models to ones that have been built to connect with other issue areas, like those of IAMs. The earlier discussion of IAMs in Section 3.2 already noted some of the major economic models associated with them. For instance, it identified the MACRO model that is used in analysis with the MESSAGE energy model. Like many economic models, MACRO has gone through multiple generations and adaptations (it was originally adapted from Global2100 [also called ETA-MACRO]).[11] Section 3.2 also identified MAGNET (Modular Applied GeNeral Equilibrium Tool), which is built around the standard GTAP model and is a successor to LEITAP, as an element of the IMAGE suite (see Woltjer and Kuiper, 2014).

Although many such economic models in IAMs grew out of the CGE tradition and build on software and data specialized for it, their long-term focus demands attention also to growth dynamics. The manner of representing growth can vary dramatically.[12] In some cases, economic growth, or at least global productivity, is completely exogenous. When it is endogenous, one approach is to combine representation of advance in the technology or productivity of one or more system leaders with rates of catch-up by other countries that are conditional on a variety of factors. Among IAM economic models that represent convergence are some in the RoSE project (Kriegler et al., 2013, p. 11; Kriegler et al., 2016) and two of the three models that provide economic forecasts for the Shared Socioeconomic Pathways (SSPs), namely those of the OECD (Château et al., 2014, p. 31) [13] and IIASA (Cuaresma, 2017, pp. 227–228).[14]

Still again, the most important determinant of growth in the long term is arguably productivity, especially in a century during which technological change screams its importance in advances ranging from artificial intelligence and robotics through renewable energy forms to biotechnology, and during which educational advance is on a strong march. Therefore we can expect that both standalone economic models and those imbedded in IAMs will (and must) make their treatment of productivity increasingly sophisticated.

6.1.3.2 *Enhancing the Treatment of Productivity*

A broad literature on endogenously explaining productivity advance has grown up over recent decades (Aghion and Howitt, 1992; Grossman and Helpman, 1994; Romer, 1990; 1994; see Hughes, 2007 for an extended discussion). Empirical analysis of economic growth, even when not specifically focused on productivity, has augmented that literature (Aghion and Durlauf, 2005; Barro, 1999; Barro and Sala-i-Martin, 2004). More recently, there has been strong interest in the roles that structural change (growth of manufacturing and service sectors) and formalization of informal activity play in enhancing productivity growth

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[11] See https://wiki.ucl.ac.uk/display/ADVIAM/Macro-economy+-+MESSAGE for information about MACRO.

[12] Kriegler et al. (2015, p. 26, and pages 7–12 in supplemental material) identified most of the IAMs discussed in Chapter 3 and provided some information related to treatment of growth.

[13] Leimbach et al. (2017) noted the empirical complications of this convergence representation.

[14] In a much simpler model used for a PricewaterhouseCoopers (PwC) report, Hawksworth and Chan (2015, p. 35, 36, 38) also used a convergence representation of productivity, conditional upon physical and human capital investment, political stability, openness to trade and investment, rule of law, and other factors.

(de Vries et al., 2012; Gehringer et al., 2016), a thrust that to some degree represents a throwback to attention given structural change by Chenery (1979) and other work of an earlier period.

Arguably still in the early stages of elaboration, the literature on endogenous productivity advance has led to the linkage of research and development spending to productivity in macroeconomic modeling, an approach of both WorldScan (Lejour et al., 2006, p. 9, 27) and GEM-E3 (Capros et al., 2013, p. 12). Similarly, endogenous change in technological advance has emerged in modeling of energy, for instance in the MERGE-ETL system where a learning curve approach is used (Kypreos and Bahn, 2003, p. 250); that is, costs decrease as installed capacity—a proxy for learning across both the technology and production processes—increases.

There are additional ways in which productivity can be endogenized. In the World Bank's LINKAGE model, it responds to export share of total output (van der Mensbrugghe, 2011, p. 46). Similarly, in the World Bank's MAMS system it responds to trade openness and government (apparently infrastructure) capital stocks (Lofgren and Díaz-Bonilla, 2010, p. 75).[15]

Among the most ambitious and comprehensive attempts to endogenize forecasts of productivity is that of the Conference Board[16] (Erumban and de Vries, 2016, pp. 15–23), with forecasts to 2026 that specify total factor productivity as a function of human development (life expectancy and average years of education), R&D spending, corruption, and economic globalization. The Conference Board TFP representations depend on externally obtained future values of some of the drivers (life expectancy and education), assume constant growth rates for others (R&D spending), and leave still others unchanged (corruption and globalization).

At this stage in model evolution, as useful as the current generation of recursive dynamic CGE models is, most forecasting of productivity tends to incorporate endogenous representation only of limited drivers of it. There is considerable room for improvement, given the importance of analysis concerning the future of human, social, and sustainable development. More generally, the obvious real-world functioning of feedback loops connecting policy initiatives (like those in pursuit of SDGs) and economic growth highlights the need for a modeling approach in which (1) economic, demographic, and sociopolitical modules are integrated, and productivity growth responds to a wide range of demographic and sociopolitical changes and (2) productivity and growth then feed back to these other systems.

With respect to feedback, and given their focus on climate change, some IAMs link such change back so as to modify an otherwise exogenously specified rate of change in productivity. In early efforts, that linkage tended to be fairly simple, albeit nonlinear. WorldScan (Lejour et al., 2006, pp. 99–101) linked spending on abatement back to total factor productivity of emitting sectors. As van der Mensbrugghe noted (2010, p. 4, 31, pp. 35–37) in the context of discussion of the World Bank's ENVISAGE model, the linkages, while still focused on climate change, have become more multifaceted and complex, for instance by breaking out the impact of sea-level change specifically. ENVISAGE began with a linkage of climate change to

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[15] Lofgren and Diaz-Bonilla also suggested (Lofgren and Díaz-Bonilla, 2010, p. 125, fn. 28) that it would be possible to include health effects on productivity of labor, but they did not do so because of lack of estimates in the quantitative relationship.

[16] See https://www.conference-board.org/.

agricultural productivity (looking to the analysis of Cline, 2007 as IFs has done; see Section 7.1.4.1). ENVISAGE now incorporates a much broader range of climate change impacts, including on health, tourism, water availability, household energy consumption, and multifactor productivity.

6.1.4 Economics in IFs

International Futures sits within the hybrid economic modeling tradition with an equilibrating SAM structure (Hughes and Hossain, 2004) based heavily on GTAP data, and with a recursively dynamic and endogenous representation of long-term economic growth. The SAM structure facilitates attention to opportunities and constraints around government finance that link closely to the education, health, and infrastructure models of IFs as well as to income distribution and poverty. IFs, perhaps uniquely, also represents a basic version of a stock SAM showing assets and liabilities as a supplement to the traditional accounting matrix of flows; the stocks are a key element of dynamic behavior. The IFs project gives great attention to making MFP endogenous. The endogenous productivity and growth representation benefits from the SAM and from the connection of all the models in IFs (see again Section 4.1).

The system includes other unique features, including an approach to chasing equilibrium over time in goods and service markets, domestically and internationally, rather than computing it in every time step. The discussion that follows focuses heavily on production and supply sides of the model; more extensive (but not always fully up to date) documentation can be found at https://pardee.du.edu/wiki/Main_Page.

6.1.4.1 The IFs Approach to Productivity

The core calculation on the supply side is of value added (*VADD*) by sector, the sum of which is GDP (see again the discussion of Table 6.1). The function in IFs has the Cobb–Douglas form, driven by cumulative stock values of sector-specific technology or multifactor productivity (*TEFF*), capital (*KS*), and labor (*LABS*). Our formulation also takes into account the level of capacity utilization (*CAPUT*), initially set exogenously (***caputtar***). In a multisector model such as IFs, the functions also require sectoral exponents for capital (*CDAlfS*) and labor that, assuming constant returns to scale, sum to 1.0 within sectors. (See Box 5.1 for equation notation used throughout this volume.)

$$VADD_{r,s} = CDA_{r,s,t=1} * TEFF_{r,s} * CAPUT_{r,s} * KS_{r,s}{}^{CDAlfS_{r,s}} * LABS_{r,s}{}^{\left(1-CDAlfS_{r,s}\right)}$$

$$s = 3,4\ldots n\,\mathit{sector}\left(\begin{array}{r}\textit{in agriculture and energy sectors, physical partial}\\ \textit{equilibrium models determine value added}\end{array}\right)$$

where

$$CDA_{r,s,t=1} = \frac{VADD_{r,s,t=1}}{\left(KS_{r,s,t-1}\right)^{CDAlfS_{r,1,t=1}} * \left(LABS_{r,s,t=1}\right)^{\left(1-CDAlfS_{r,s,t=1}\right)}}$$

$$CAPUT_{r,s,t=1} = \boldsymbol{caputtar}$$

PRODUCTIVITY OVERVIEW: EXOGENOUS AND ENDOGENOUS ELEMENTS

In IFs, the total productivity stock factor (*TEFF*) is the accumulation over time of annual values of growth in multifactor productivity (*MFPGro*).

$$TEFF_{r,\ s} = TEFF_{r,\ s,\ t-1} * (1 + MFPGro_{r,\ s})\ where\ TEFF_{r,\ s,\ t=1} = 1.0$$

The specific manifestation of the production function in IFs, with a very significant elaboration of *MFPGro*, is unusual in long-term economic forecasting. Its characteristics make it the focal point of the impacts that human development, social development, and knowledge advance have on economic growth; thus it is at the core of linkages across many of the models in IFs.

It is helpful to conceptualize the representation of productivity in IFs in terms of distal and proximate drivers. The distal driver is technology/knowledge advance. We differentiate that, in turn, into (a) the advance of technology leader(s) at the global system frontier and (b) the catch-up or convergent advance of countries behind that frontier. The proximate drivers are a large set of factors discussed later that act as accelerators or decelerators of productivity growth of all countries, including system leaders. As is typical in IFs formulations with both distal and more proximate drivers (see especially the health model discussion of Section 5.2.4), it is important to control for the distal drivers in the representation of the impact of proximate ones.

Concretely, the annual growth in MFP (*MFPGro*) consists of a base rate linked to systemic technology advance and convergence (*MFPRATE*), plus the four more proximate terms that cause MPF growth to accelerate or decelerate over time: (1) human capital (*MFPHC*), (2) social capital (*MFPSC*), (3) physical capital, such as infrastructure (*MFPPC*), and (4) knowledge capital including R&D investment (*MFPKN*).

$$MFPGro_{r,s} = MFPRATE_{r,s} + MPFHC_r + MFPSC_r + MFPPC_r + MFPKN_r$$

Elaborating MFPRATE first, we represent the underlying technological advance of the systemic leader, by default set to be the United States, via an economic sector-specific exogenous parameter (***mfpleadr***). The distal representation of the basic convergence process draws on a function with an inverted U-shaped form against GDP per capita. It thereby represents the great difficulty that very low-income countries have in adapting technology from the frontier, the increasing ease of that for middle-income countries, and the decrease in the convergence rate as countries approach the GDP per capita of the leader. The inverted U-function generates a technological advance premium (*MFPPrem*). The model user can change both the ***mfpleadr*** parameter and the *MFPPrem* function. (See Hughes, 2007, 2015 for further description of the technology leadership and technology convergence functions.)

The calculation of MFPRATE requires a correction so that the growth rate in the first year is consistent with the growth in sectoral value added that is not explained by contributions of technological advance in the leader or by the convergence to the leader. In fact, IFs uses two correction factors. The first is a global factor (*MFPGloCor*) that is a gross adjustment to assure that the initial calculation of all *MFPRATE* values globally are consistent with global economic growth. That global adjustment is carried forward across time. The second is a country- and sector-specific correction factor (*MFPCor*) computed to assure that the rate of productivity growth in each country-sector is consistent with the growth that is unexplained by capital and labor growth in the first model-run year. That correction factor converges to zero over the number of years specified by ***mfpconv***. This convergence assumption has significant implications for model behavior because it tends to slow down growth in countries (like China) that have had a burst of growth beyond that which the rates of the leader and the catch-up factor would lead us to anticipate, and to speed up growth in countries (like the transition states of Central Europe) that earlier suffered deceleration similarly unexpected by the basic formulation.

$$MFPRATE_{r,s} = \boldsymbol{mfpleadr_s} + MFPrem_r + MFPCor_{r,s} + MFPGloCor_{t=1} + \boldsymbol{mfpbasgr} + \boldsymbol{mfpbasinc} * zy + \boldsymbol{mfpadd_r}$$

where at $t=1$

$$MFPPrem_{r,t=1} = Function(GDPPCP_{r,t=1})$$

$$MPFComp_{r,t=1} = MPFHC_{r,t=1} + MFPSC_{r,t=1} + MFPPC_{r,t=1} + MFPKN_{r,t=1}$$

$$MFPGro_{r,s} = F(GroRate_{r,s}, KS_{r,s}, LABS_{r,s})$$

$$MFPGloCor_{t=1} = \frac{\sum_{r=1}^{R}\sum_{s=1}^{S}\left(MFPGro_{r,s,t=1} - \boldsymbol{mfpleadr_s} - MFPrem_r - MPFComp_r\right) * VADD_{r,s,t=1}}{\sum_{r=1}^{R}\sum_{s=1}^{S} VADD_{r,s,t=1}}$$

$$MFPRATE_{r,s,t=1} = \boldsymbol{mfpleadr_s} + MFPrem_r + MFPGloCor_{t=1}$$

$$MFPCor_{r,s,t=1} = MFPGRO_{r,s,t=1} - MFPRATE_{r,s,t=1}$$

and at $t>1$

$$MFPPrem_r = Function(GDPPCP_r)$$

$$MFPGloCor_t = MFPGloCor_{t=1}$$

$$MFPCor_{r,s,t} = (ConvergeOverTime(MFPCor_{r,s,t=1}, 0, \boldsymbol{mfpconv})$$

In addition to the basic technology terms and the correction factors here, there are three parameters in the *MFPRATE* equation (with zero values as the default) that allow the model user much control over assumptions of technological advance. The first is a basic parameter (***mfpbasgr***) that allows a global growth increment or decrement, and the second is a parameter (***mfpbasinc***) that allows either a constant rise or slowing of growth rate globally, year by year, where *zy* is the count of the model-run years across time. The final parameter, ***mfpadd***, allows flexible intervention specific to any country or country grouping.

ENDOGENOUS PRODUCTIVITY GROWTH

What makes the IFs economic model unique is the representation of the proximate driver contributions brought into the representation of *MFPGro* as accelerators/decelerators. That is, IFs represents multiple variables that affect the productivity growth process, in the categories of human, social, physical, and knowledge capital. Development literature understands that multiple variables affect the process, but modeling does not often represent a large set of them in interaction.

The IFs approach has roots in two complementary literatures: that around convergence, and that around structural patterns of development. Much *convergence literature* points to roots in the Nelson and Phelps (1966) model of technology diffusion facilitated by human capital (see also Benhabib and Spiegel, 1994, 2005). That model posits that countries catch up with the systemic technological leader dependent upon their level of human capital, with a special emphasis on education. Formulations differ with respect to whether convergence is exponential or logistic, with the latter producing, as in IFs, slower catch-up of countries both furthest from and closest to the leader in productivity levels.

The *structural development literature* recognizes that there is a tendency for most developmentally supportive variables to advance in a rough relationship with each other and with GDP per capita (as identified in structuralist literature such as Chenery and Syrquin, 1975; Kuznets, 1955, 1959; Sachs, 2005; and Syrquin and Chenery, 1989). This pattern of structural change can help us think about contributions to productivity at specific points in time as well as its change across time. If, in any given year, a variable such as formal education attained by adults exceeds the typical or expected value for a country at a given level of GDP per capita, we can reasonably expect that the variable is helping boost productivity. However, the picture becomes somewhat more complex in dynamic modeling across time. For example, even in a country where adult education levels are high and advance steadily, those advances might not keep pace with the advance in other developmentally supportive variables from health to infrastructure; in such a country, even steadily improving education levels might shift from accelerating rise in productivity to slowing the rate of productivity growth.

The basic formulations of IFs, while building on distal patterns of technological advance and convergence, are tied at the proximate level (and therefore at the policy-relevant level) to the structuralist literature. The general logic of each of the four driver clusters around human, social, physical, and knowledge capital is the same. Each cluster aggregates several variables that generally contribute to productivity. This recognizes that, for instance, different formulations in the literature specify education in terms of spending on it, enrollment levels, adult attainment, or quality, with many (as does IFs) focusing heavily on attainment (Pelinescu, 2015). It is the difference between expected and actual values for each variable in the cluster, and the relative pace of their change, that gives rise to an incrementally positive or negative contribution to productivity growth.

AN EXAMPLE: HUMAN CAPITAL AND PRODUCTIVITY

In the human capital cluster, there are seven variables that can add to or subtract from the human capital (*MFPHC*) term:

- education spending contribution (*EdExpContrib*)
- average years of adult education contribution (*EdYearsContrib*)
- education quality contribution (*EdQualContrib*)
- boost from life expectancy years (*LifExpEdYrsBoost*) assumed to generate (via ***mfpedlifexp***), inter alia, extra impact of years of adult education in a society
- stunting contribution (*StuntContrib*) related to earlier undernutrition of children
- disability contribution (*DisabContrib*) related to morbidity from the health model
- vocational education contribution (*EdVocContrib*) resulting from growth or decline in vocational share of lower and upper secondary enrollment

Contributions from the first five of these seven drivers have parallel formulations. Values computed in IFs—often as a result of extended formulations and often from other models in the system (as with life expectancy, computed in the health model)—are compared with an expected value. The first five expected values (*EdExpComp*, *EdYrsComp*, *EdQualComp*, *LifExpComp*, and *StuntingComp*) are functions of GDP per capita at purchasing power parity (PPP) and potentially also from other variables (such as adult education attainment for expected education quality). In the case of disability, the expected value is set to the world average level (*WorldDisavg*). For vocational education, the model relies on exogenous scenario assumptions rather than an elaborated forecasting formulation, and for an expected value relies on a moving average of its extent. Because of the recursive structure of IFs, some terms (e.g., expenditure on education) rely on variables from the previous time step, adjusted with a growth assumption tied to a moving average of longer-term GDP growth (*IGDPRCor*).

$$MFPHC_r = EdExpContrib_r + EdYrsContrib_r + EdQualContrib_r + LifExpEdYrsBoost_r \\ + StuntContrib_r + DisabContrib_r + edVocContrib_r$$

where (illustratively, other contributions are parallel):

$$EdExpComp_r = F(GDPPCP_r)$$

$$EdExpContrib_r = \left(\frac{GDS_{r,g=EDUC,t-1} * (1 + IGDPRCor_r)}{GDP_{r,t-1} * (1 + IGDPRCor_r)} * 100 - EdExpComp_r \right) * \boldsymbol{mfpedspn}$$

OTHER ENDOGENOUS PRODUCTIVITY TERMS

In very similar fashion, six factors contribute to the social capital *(MFPSC)* term:[17]

- economic freedom, as in the Fraser Institute measure
- government effectiveness, as in the World Bank measure
- corruption, as in the Transparency International measure
- democracy, as in the Polity Project measure
- freedom, as in the Freedom House measure
- conflict, as in the IFs project's own measure, tied in turn to the work of the Political Instability Task Force

Evidence is very mixed with respect to whether democracy facilitates economic growth (Barro, 1996; Halperin et al., 2004; Joshi, 2011; Przeworski et al., 2000; Przeworski and Limongi, 1997); accordingly, in IFs the default value of the parameter on that term is zero. There is much less debate as to whether internal stability and security have positive impacts on growth, especially when one considers the extremely negative implications for economies

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[17] For more information on the measures that IFs draws upon see: https://www.fraserinstitute.org/studies/economic-freedom; http://info.worldbank.org/governance/wgi/pdf/wgi.pdf;
https://www.transparency.org/news/feature/corruption_perceptions_index_2017;
http://www.systemicpeace.org/polityproject.html;
https://freedomhouse.org/report-types/freedom-world; and
http://www.systemicpeace.org/inscrdata.html.

of full-blown state failure. IFs contains variables both for domestic instability short of conflict and for the probability of overt conflict (both discussed later in this chapter). The expected value for the former is a function of GDP per capita at PPP and that for the latter is each country's value in the initial model year.

The logic of the physical capital (*MFPPC*) cluster is again parallel to that of the human and social capital clusters, involving the comparison of the value computed in IFs with an expected value. The standard form involves four contributions:

- traditional infrastructure index (patterned after Calderón and Servén, 2010)
- Information and Communication Technology (ICT) infrastructure index (IFs index)
- spending level for other infrastructure
- the price of energy (included because higher prices of energy can make some forms of capital plant no longer efficient or productive)

In the case of the physical capital cluster, only the expected values of the IFs traditional infrastructure index and other infrastructure spending are computed as most other cluster elements are, namely as a function of GDP per capita at PPP. ICT technology has been evolving so rapidly that there is not a basis for an expected value tied to GDP per capita. Instead, the expected value of the ICT index reflects a moving average of change over time, and the contribution of ICT to MFP is based on the model's computation of index advance relative to that moving average. For the energy price term, the "expected" value is set equal to the energy price in the first year of the model run.

Following the pattern of other MFP driver clusters, the one for knowledge accumulation (*MFPKN*) includes three terms that compare computed model values versus typical or expected values, and then uses parameters to translate the differences into increments or decrements of MFP. The three terms represent:

- R&D spending
- economic integration via trade with the rest of the world
- the share of science and engineering among all tertiary degrees earned

For the first and third terms, the expected value is a function of GDP per capita at PPP. However, there is no clear “expected” relationship between extent of economic integration and GDP per capita, so the model compares the most recent value of trade openness (exports plus imports as a percentage of GDP) with a moving average of it; thus, surges or drops in openness affect productivity. Given the extreme global range of trade openness, the elasticity term itself is variable in this relationship, with values decreasing when openness is greater (that is, countries that start with less openness gain more from the same percentage point increases in it).

INFORMALITY

The informal economy provides a livelihood for the majority of people in low- and lower-middle-income countries, and thus it deserves attention that it almost never receives in economic modeling and forecasting. The IFs project builds on data primarily from the OECD, the International Labor Organization, and Women in Informal Employment: Globalizing and Organizing (WIEGO),[18] as well as on estimates by Schneider and Enste (2000) of the

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[18] Available at http://www.wiego.org/.

related shadow economy, to create an integrated database as a foundation for initializing and forecasting informality as a portion of the labor force (*LABINFORMSHR*) and of GDP (*GDPINFORMSHR*).

Although there are many variants, two alternative viewpoints generally color discussion of the informal economy (see Andrews et al., 2011; Loayza, 2016; Oviedo et al., 2009). In the *survivalist perspective*, informality provides for basic needs, especially in developing economies with weak formal sectors. In the *entrepreneurial perspective*, informality offers an escape from regulation and taxation, even in higher-income countries. These models informed our own integrated empirical analysis and formulations in IFs (Bohl et al., 2017). The formulation again combines a distal driver (years of adult education) with more proximate ones: regulation, taxation, corruption, government to household transfers, and R&D level.

Our analysis of informality further focuses on the potential benefits of formalization, especially the typically higher productivity of the formal sector and the ability of governments to secure revenue from formal activity and therefore support expenditures, including those on education, health, and infrastructure. That analysis needs to recognize that the leverage that countries have to effect formalization may be modest, especially in lower-income countries where the motivation for informality is survivalist.

PHYSICAL ENERGY SHORTAGES

One could build a model in which physical shortages of energy proportionately constrained value added relative to potential production. Yet economists typically do not accept such shortages as a real-world phenomenon because, at least in theory, prices rise to clear markets. However, in temporary periods (like the 1970s when governments intervened in those markets), such shortages do actually appear. Long lines at gas stations and proscriptions on driving on certain days reflect allocation in the face of shortages, not market equilibration via price—the theoretical market clearing (or shadow) price is not an adequate model substitute for such shortages. Accordingly, in disequilibrium situations, IFs assumes that energy shortages, as a portion of domestic energy demand and export commitments, lower actual production in all sectors through a physical shortage multiplier factor. A parameter/switch (***squeeze***) controls this linkage and can turn it off.

6.1.4.2 Flows and Accounting

IFs wraps the representation of productivity and growth in a full social accounting matrix structure that chases equilibrium over time. This includes treatment of the demand side of the economy (including allocation to investment), and of trade, finance, and equilibration itself. We begin with flows (domestic demand and foreign accounts) and then move to equilibration.

Government revenue and expenditure streams are diverse and important because they help connect a variety of the models in the IFs system; because of this, a subsequent section of this chapter discusses government finance at some length rather than it being considered here. It is, of course, a critical component of productivity and growth.

DOMESTIC FLOWS AND THE DEMAND SIDE

A foundational element of the demand side is passing through the returns of labor and capital to households and firms and computing income for each, some of which is taken by government in taxes. The computation of income is refined by the division of households into skilled and unskilled categories, using data from GTAP to determine their respective contributions to value added.

Households then make decisions about the trade-off between savings and consumption and about what to consume. The IFs approach follows Modigliani (1986) in conceptualizing life-cycle savings and consumption patterns, and it draws on sources in Lee and Mason (2011) for its empirical foundation. With respect to consumption patterns, with rising income decreasing shares go to food and increasing shares to services (other sectoral patterns also change), and Engel elasticities direct those changing shares in IFs in a linear expenditure system (Taylor, 1979, pp. 219–223).

Firms make investment decisions. Gross capital formation or investment in IFs is calculated from an investment rate applied to GDP; the investment rate itself responds to interest rates in equilibration with savings. Sectoral investment demand in IFs is responsive to inventories, and investment is allocated across sectors proportionately to that demand. Gross capital formation (investment except for inventory change) augments depreciated capital stocks. The model does not keep track of the vintage or age of capital, a limitation in our representation of it.

EXTERNAL ACCOUNTS

The basic element is trade, represented with responsiveness to domestic relative prices and international exchange rates, as well as to gross production (for exports) and domestic demand (for imports). For computational efficiency, IFs uses a pooled rather than bilateral or dyadic approach to trade as a default; dyadic representation is available as an option. In addition, there are other international financial transactions:

> *Foreign aid.* The percentage of GDP given by donors is constant or changed exogenously. Receipts of each country from the pool of aid are allocated proportionately to initial share, subject to exogenous change and to shifts of aid over time toward the lowest-income countries (as others need less aid). The aid is divided between grants and loans, with repayment of the latter required over time.
>
> *Worker remittances*. Levels are tied to numbers of foreign nationals in a recipient country, initial data on remittance flows from and to countries, and changes in the GDP per capita of host countries.
>
> *Foreign direct investment and portfolio flows*. Again, IFs uses a pooled approach, rooted in sending and receiving patterns in the model base year. There are also cross-sectional estimations of the relationship between levels of sending and receiving as portions of GDP; these estimations serve as targets over time toward which individual country patterns move, thereby building in the possibility of evolution from net recipient to net provider.
>
> *International financial institution flows.* The World Bank and IMF provide loans, including concessional ones, and early-year patterns in those shape future patterns in IFs (modifiable exogenously). Amounts are relatively small compared to other flows.

6.1.4.3 Equilibration Dynamics

IFs is fundamentally a dynamic recursive general equilibrium model, but one that recognizes that imbalances always exist in a world that is chasing, rather than in, equilibrium. There are five imbalances that the model tracks and uses to signal need for change to both sides of the imbalance:

- *Inventories (stocks of goods and services)*. Although stocks of services do not actually exist, maintenance of a shadow-like variable in the model works in parallel to those of goods. Inventories below a targeted share of gross production raise sectoral prices, and those above the targeted share lower them.
- *Labor supply and demand*. Labor supply is a function of age structure and participation rates, with special attention to female participation. Labor demand per unit of value added tends to decline with GDP per capita. A wage index representing changes relative to those of GDP per capita equilibrates supply and demand. The model distinguishes skilled and unskilled labor.
- *Imbalance of savings and investment*. This imbalance interacts with that on goods and services and affects interest rates (the price of money).
- *External debt (or assets)*. In IFs, a country's current account balance with the rest of the world consists of net exports plus net aid receipts and net worker remittance receipts, minus principal and interest paid on international indebtedness. Negative current account balances contribute to accumulating stock of international debt and positive ones to assets. The ratio of debt to GDP affects the exchange rate, the price of a country's currency.
- *Government debt (or assets)*. Imbalances in this relative to a targeted level provide feedback to revenues and expenditures via factors proportional to the imbalances. The next section elaborates government finance.

The lurching search for equilibria over time must avoid extreme overshoot or undershoot in the equilibrating (e.g., prices or exchange rates) and equilibrium-monitoring variables (stocks such as inventory levels and international indebtedness to GDP ratio). IFs relies on an adjustment mechanism for equilibrating variables that is often used in engineering and is sometimes called a PID controller. That is, the adjustment process responds *proportionately* to the *integral* of the error (the stock discrepancy) and the *derivative* of the error (the year-to-year change in error term). For more information, see Chang, 1961 and Mishkin and Braun, 1961. The IFs use of this mechanism builds upon its implementation by Thomas Shook in the World Integrated Model project (Mesarovic and Pestel, 1974).

The PID system compares the level of the equilibrium-monitoring variable with a targeted level and adjusts the equilibrating variable (such as domestic relative prices, interest rates, exchange rates, wage rates, or the multipliers on government revenues and expenditures). The comparison has two terms in IFs (variable and parameter names shown here are generic and vary across IFs uses). The model first computes a difference (*Diff1*) between the actual and desired levels for the equilibrium monitoring variable and scales that difference with a scaling base (*ScalingBase*) value (for instance, total production, demand, or their sum in an economic sector might be reasonable scaling bases against which to gauge the importance of a deviation of inventories from desired levels). In addition, the adjustment mechanism uses a second order difference (*Diff2*) to compare the level of the equilibrium-monitoring variable with its value in the previous time cycle, relying upon the same scaling base. Nonzero differences result in a multiplier value (*Mul*) that deviates from 1.0 depending on the magnitude of two elasticities (***el1*** and ***el2***) and is applied cumulatively to the equilibrating variable for feedback via elasticities to the supply and/or demand sides.

$$Mul = \left(1 + \frac{Diff1}{ScalingBase}\right)^{\boldsymbol{el1}} * \left(1 + \frac{Diff2}{ScalingBase}\right)^{\boldsymbol{el2}}$$

IFs represents this mechanism in a function called the adjuster (*ADJSTR*) that the model calls upon in the multiple equilibrating processes. The magnitude of the two parameters will, of course, differ depending on the model variable in which equilibrium is being pursued and the scaling base. Experience has shown, however, that ***el1*** normally takes absolute values between 0.2 and 0.4, while ***el2*** is most often two times the value of ***el1***, and thus varies most often between 0.4 and 0.8. The values of ***el1*** and ***el2*** are determined experimentally by model area in order to be large enough to maintain approximate equilibrium and small enough to avoid unreasonably rapid or extreme oscillation. There will inevitably be some oscillation in equilibrium-seeking processes, and in some cases (such as inventory levels), the parameters could be set to provide an oscillation consistent with known cycles, such as business cycles. Because IFs is a long-term rather than short-term model, however, we have generally devoted little attention to tuning the oscillation cycle, focusing instead on long-term stability in the face of shocks introduced by scenarios of model users.

This general equilibrating approach is used in several models within the IFs system, including the economic model, the representation of government finance, and the two elaborated physical sectoral models discussed in the next chapter (agriculture and energy).

6.1.4.4 Income Distribution and Poverty

Indicators of distribution and poverty build on production and flows; Hughes et al. (2009) elaborate the modeling approach and analysis of the IFs project. Within countries, IFs computes a Gini coefficient from a Lorenz curve tied to the relative shares of income that skilled and unskilled households receive and the respective population assigned, via education level, to the two household categories; IFs raises the education level required for assignment to the skilled category as the average education of the adult population rises.

The structurally based Gini forecasts built this way suffer from the use of only two household categories, when many more would be desirable, and from the relatively subjective algorithm that changes category assignment with education levels. As economies develop, the education that once might have created a skilled worker (even just basic literacy) might no longer suffice. Thus, in analysis at the country level, the project relies more on exogenously specified assumptions about Gini change than on endogenous calculation. At the global level, our confidence in understanding inequality is much greater because the long term is dominated by intercountry differences in average GDP per capita rather than intracountry change.

Given Gini, the GDP or household consumption per capita, and an assumption of the shape of the income distribution (posited in IFs and much literature to be roughly lognormal, even though it can be bimodal or have other forms in some countries), it is possible to compute the portions of the population below or above any specified GDP or per capita consumption level. This allows representation of the portion of the population below globally monitored poverty lines and the portion between any exogenously specified levels (such as boundaries of the middle class).

6.1.4.5 Limitations

AROUND THE SAM

Beyond populating SAMs with data, there are, of course, many other challenges that surround the use of SAMs in forecasting. There are also approaches to addressing them, some of which are already used in IFs.

Creating a sectoral structure appropriate for the project. In IFs, we use a concordance table to reduce the GTAP sectoral data from 57 sectors to just six (agriculture, energy, other primary materials, manufactures, services, and ICT), although the system allows changes in the definition of those six. A needed extension is the capacity to increase the number flexibly, minimally to divide manufactures and services into those with lower and higher technology elements.

Making the coefficients dynamic. The cells in the input-output matrix (see again Table 6.1) tell us more than the gross values of flows across sectors. The ratios of inputs to outputs represent the technological structure of the economy. That structure varies across countries and time. IFs perhaps uniquely represents one of the key dynamics driving such variation, namely the changes in technology with development, using GDP per capita as a proxy. To do so, the IFs data preprocessor (Hughes and Irfan, 2013) computes averages of GTAP input-output coefficients across countries at variable levels of GDP per capita, and as countries increase GDP per capita the model interpolates across the matrices and shifts economies to what presumably are more advanced technological structures. This does not, however, capture the systemic temporal changes in global technology. Because GTAP has had eight releases over time, there is an increasing basis (that we have not yet mined) for analysis and use of changing structure at constant levels of GDP per capita.

Representing country-to-country (bilateral) flows. The use of SAMs for each country, and their connection via trade and financial flows, allows the building of a globally universal SAM (Vos, 1989), and IFs has such a structure. However, one problem in creating it is the representation of country-to-country bilateral flows. Dyadic data series are available for trade and increasingly for migration and for foreign direct and portfolio investment. However, forecasting of bilateral flows is complicated, and the common approaches to doing so tend to (a) build in very high levels of inertia in the intercountry patterns (as Armington coefficients do for trade; see Armington, 1969) and/or (b) assume very simplistic drivers of change, such as the total economy or monadic trade values that drive simple gravity models. Further, unless there are significant sociopolitical linkages to bilateral flow information, such as understanding how trade might affect political relations (or, more likely, be affected by those), there is not always a rationale in long-term forecasting for paying the computational cost of making trade, investment, or migration bilateral. The default IFs system instead uses a pooled approach to forecast intercountry flows of trade, financial aid, investment, and migration. That is, it puts all outflows and all inflows into global pools, balances the sums, and does not represent country-to-country flows. However, the project has increasingly gathered historical data on many types of bilateral flows and relationships and has developed optional formulations for forecasting those. These are first steps toward more bilateral representation and tying that to political relationships.

Stock and flow interactions. Most modeling with SAMS treats only flows, but underlying any SAM of flows is implicitly a second SAM of stocks, including the domestic and international debts and assets of each actor category. At least some basic representation of these is essential in long-term forecasting to track and accumulate disequilibrium over time as a basis for price signals and adjustment. For example, governments cannot spend large amounts beyond their revenues without building up debts that will ultimately constrain that spending or require revenue increase, and firms cannot borrow investment funds internationally without accruing debts that might ultimately prove unpayable by them and might create major foreign exchange problems for their societies. While systemic information on these stock variables is very scarce relative to flows, disequilibria in the stock variables characterize almost all countries in a model base year. Thus we have built a basic "stock SAM" in IFs that underlies the flow SAM. It can at least track changes in those stocks from the model's base year, even if those are poorly initialized, and can feed back signals that change flows over time (rather than forcing equilibria every year) in response to stock imbalances.

THE LES APPROACH FOR CONSUMER DEMAND

Although a linear expenditure system (LES) structure with Engel elasticities like that in IFs is often used to represent changing patterns of household consumption with income level,[19] it is an approach much better suited to short-term than long-term forecasting. In the future IFs will move to a structural approach that represents changing shares of consumption across primary, secondary, and tertiary economic sectors tied to relationships with income levels. Doing so would provide much more consistency across countries undergoing major changes in income over the longer run.

PARAMETERIZATION OF TERMS DRIVING MFP ENDOGENOUSLY

Although our approach to calculation of MFP creatively connects developments in many other models in the IFs system to it, parameterization of the effects individually and in interaction is complicated and uncertain. Hughes (2005) documented the original creation of the structure and its parameterization based on existing literature and our own analysis. There are such literatures concerning all of the major variables driving MFP in IFs that Section 6.1.4.1 discussed. To illustrate, consider some of the literature linking contributions from education to MFP using different driving variables and generating various findings:[20]

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[19] Ernst Engel (1821–1896) first observed that food expenditures decline as a portion of income with rising income levels, known as "Engel's law." See https://en.wikipedia.org/wiki/Engel%27s_law.

[20] Mankiw et al. (1992) provided one of the early extensive empirical analyses of growth. Barro and Sala-i-Martin (2004, pp. 511–566) reported cross-sectional analysis of countries with 67 variables, in which primary education in 1960 followed East Asian location as strongest correlates with economic growth. Benos and Zotou (2014) usefully surveyed 57 empirical analyses of the relationship between education and economic growth in a meta-regression analysis that reminds us of the publication bias toward positive results and reinforces conservative treatment of the relationship by the IFs project.

- Barro (1999, pp. 19–20) reported that one additional year of male secondary and higher education raised growth by 1.2% per year. Barro and Sala-i-Martin (2004, p. 524) reported that a one standard deviation increase in male secondary education raised economic growth by 1.1% per year and a one standard deviation increase in male higher education raised it by 0.5%.
- Chen and Dahlman (2004, p. 1) concluded that a rise of 20% in average years of schooling raised annual growth by 0.15% and that an increase in average years by one year raised growth by 0.11%.
- Jamison, Lau, and Wang (2005, p. 83) used the Barro-Lee measure of average years of school for males age 15 years and older, and concluded that educational advance accounted for about 14% of economic growth across 47 countries during 1965–1990.
- Bosworth and Collins (2003, p. 17) argued that each year of additional education added about 0.3% to annual growth.
- The OECD (2003, pp. 76–78) found that one additional year of education (about a 10% rise in human capital) raised GDP per capita in the long run by 4%–7%.
- Gehringer et al. (2016, p. 415), studying 17 European Union members and 13 economic sectors from 1995–2007, found the percentage of population with a secondary education to be the most important determinant of TFP within a unified framework of often-identified drivers. Specifically, they found that one standard deviation increase in that percentage increased TFP by 0.69 standard deviation.
- Baldacci, Clements, Gupta, and Cui (2004, p. 24) found that raising education spending in developing countries by 1% a year and keeping it higher added about 0.5% per year to growth rates. They also found that two-thirds of the effect of higher spending is felt within five years, but the full impact shows up only over 10–15 years.
- Hanushek, Jamison, Jamison, and Woessmann (2008: unpaginated) concluded from studying 50 countries that each year of educational attainment increased the 40-year growth rate of GDP by 0.37 percentage points. Moreover, adding data from test scores on cognitive skills boosted the portion of growth explained from one-fourth with attainment and GDP level to three-fourths (controlling for security of property rights and openness to trade reduced that somewhat).
- Hanushek and Woessmann (2010, p. 245) summarized earlier research as showing that each year of schooling was associated with 0.58% higher long-term growth, but their own research emphasized the role of quality in education.
- Hanushek and Woessmann (2015) found that one standard deviation increase in school quality raises GDP per capita by 1.4 percentage points.

The variety of empirical findings makes our model parameterization quite well informed, but drawing on many different analytical approaches makes it more ad hoc than we would like it to be.

INTERACTION EFFECTS OF CONTRIBUTIONS TO MFP

Many of the empirical studies that the IFs project draws upon focus on single variables or small sets of them that affect economic growth, and they might not fully control for others. Thus a concern in the IFs multivariate approach to drivers of MFP is the possibility of double counting of effects. The IFs project deals with this in part by selecting conservative values for parameters when studies indicate ranges of contribution of the variables to productivity and/or growth. For instance, the literature sketched previously suggests that years of adult education generate additional growth at the rate of 0.1%–0.3% per year of education (relative to the structurally expected value), while spending on education generates additional growth at the rate of about 0.3%–0.5% per extra percent of GDP spent on education. Both parameters are set in IFs on the low side of these ranges, 0.1 and 0.3, respectively (the user interface allows ease of change). Fortunately, some of the studies noted earlier analyze a number of growth drivers simultaneously, providing some insight into the issue. More consistently integrated empirical analysis would be of great help to IFs and the global modeling community.

Another concern that arises in connection with the multivariate approach to MFP, especially in the context of scenario analysis that might focus heavily on single drivers, is that a very large or extreme advance by one variable (or a small subset of variables) could have inappropriately large impacts on productivity. Given the structuralist tenet that development involves widespread and reinforcing changes across many variables, we view very large impacts from one or a small number of variables with suspicion. To limit this possibility, we created an algorithmic structure to dampen especially high positive or negative outlier contributions of any of the four cluster terms (*MFPHC*, *MFPSC*, *MFPPC*, and *MFPKN*).

THE REPRESENTATION OF INCOME DISTRIBUTION

Rather than a calculation of Gini that draws on the distribution of income to skilled and unskilled labor, it would be possible to use an approach to forecasting domestic income distribution that has a simpler, less structural, and more causal and statistical foundation. For instance, we could build on the notion that societies move through stages from low inequality when very poor, to high inequality when becoming richer, and to low inequality again when rich. Unfortunately, neither longitudinal nor cross-sectional analyses have consistently supported that inverted V-shape of the so-called Kuznets curve.

Alternatively, it is also possible to do a more extensive statistical analysis of the possible drivers in order to develop a multiple regression model to project inequality (see Rao et al., 2018; Sauer et al., 2016). These potential drivers include deep developmental variables such as education levels, GDP per capita, and the structure of technology and the economy (for example, heavy raw material export dependence and some emerging new technologies tend to domestically reward few, rather than many). The drivers also include more proximate variables, such as government expenditure levels. With respect to expenditures, high levels tend to facilitate transfer payments and reduce inequality, a factor already taken into account structurally in the IFs calculation of skilled and unskilled household incomes. Such statistical formulations for a variable as complex as income distribution are sometimes problematic, in part because of strong and interacting nonlinearities and also in part because of high intercorrelation (multicollinearity) of the drivers chosen. As mentioned previously, the predisposition of the IFs project is to build on structural approaches, supplemented by thoughtful use of statistics and algorithms. Yet multiple approaches to overcoming both errors of omission and commission are worthy of pursuit.

LABOR AND FINANCIAL MARKETS

The IFs demographic model, coupled with scenarios concerning retirement age, provides a reasonable basis for representing changes in labor supply. The IFs labor market uses GTAP data for change across levels of development in its formulations for possible changes in demand for labor by sector. Any representation of labor demand in the long term, however, will suffer from difficulties in anticipating the impacts of technological change, such as artificial intelligence and robotics, again probably represented best via scenarios.

IFs does represent the balance of demand and supply for investment. But it does not represent money supply and inflation. Although short-term forecasting does benefit from such representation, long-term analysis such as that in IFs cannot reasonably represent it and does not really require it.

6.1.5 Comparative Scenarios

The variables of special interest to us in economics are GDP per capita and its distribution (particularly the number in poverty). There is more variation in core scenarios of these variables across various forecasting projects than we saw around human development variables in Chapter 5. There we saw, for example, that the global population forecasts for 2100 from the United Nations Population Division (UNPD) medium variant, the IFs Base Case, and the collaborative Wittgenstein Centre for Demography and Global Human Capital and International Institute for Applied Systems Analysis (WIC/IIASA) SSP2 scenario were 11.2, 10.1, and 9.5 billion, respectively—a difference of 18% between the highest and lowest values.

In contrast, the central tendency scenarios for global GDP per capita in 2100 from the OECD SSP2, the IIASA SSP2 scenario, and the IFs Base Case are $57,200, $52,200 and $44, 600, respectively (in $2011), up from about $14,000 in 2015, reflecting a difference of 28% between the high and low values. When we turn to country-income categories, some ranges become even larger. There is much uncertainty not only about how fast the global economy is growing but also how rapidly, if at all, lower-income countries might converge to higher-income ones. Fig. 6.4 shows historical values and forecasts from the same three sources for the GDP per capita of low-income countries in 2100. There the range expands to nearly a factor of three, with the OECD numbers being especially optimistic.

It is useful to look at growth rates to see the source of some of the differences and to look at alternative scenarios as well. Fig. 6.5 shows global GDP per capita growth rates across the SSP scenarios from the OECD, putting those in context of historical patterns and adding the IFs Base Case. One point that the graphic illustrates clearly is that growth projections from global models show dramatically less year-to-year variation than do historical data. There is no meaningful way that scenarios can anticipate the annual shocks and multiple cycles that shake up such growth; moreover, the focus of global models is on long-term patterns, not annual variation. A second point from the graphic is that almost all contemporary long-term scenarios of GDP per capita growth (as well as GDP growth itself) anticipate slowing across the century.[21] One significant reason for this is that the aging of population structures will result in considerably smaller shares of the population being of working age. In the IFs Base Case, for example, the working age population declines from 66% to 59% of the global population between 2015 and 2100.

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[21] The slower growth rates from IFs in the immediate years after 2010 reflect IFs use of more up-to-date economic data than in the SSP scenarios. This is one of the advantages of the IFs preprocessor (see Section 2.2) and the project's frequent updating of initial conditions with new data and new near-term estimates from releases of the IMF's *World Economic Outlook.*

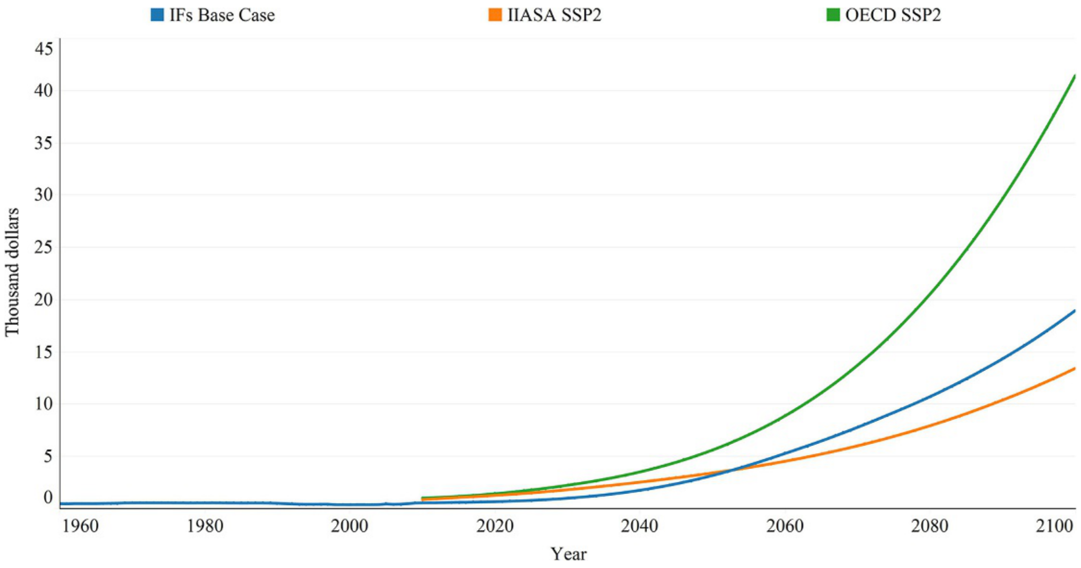

FIG. 6.4 **GDP per capita in low-income countries: History and comparative scenarios to 2100.**
Note: Uses World Bank low-income group, and compares the IFs Base Case with two Shared Socioeconomic Pathway-2 (SSP2) economic scenarios, one generated by IIASA and the other by OECD. GDP is in purchasing power parity; IFs values are in $2011 and the SSP values are converted from $2005 to $2011. Source: IFs Version 7.36; historical data from the World Bank's World Development Indicators, and IIASA and OECD comparative scenarios from SSP database (Version 1.1) hosted by IIASA at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

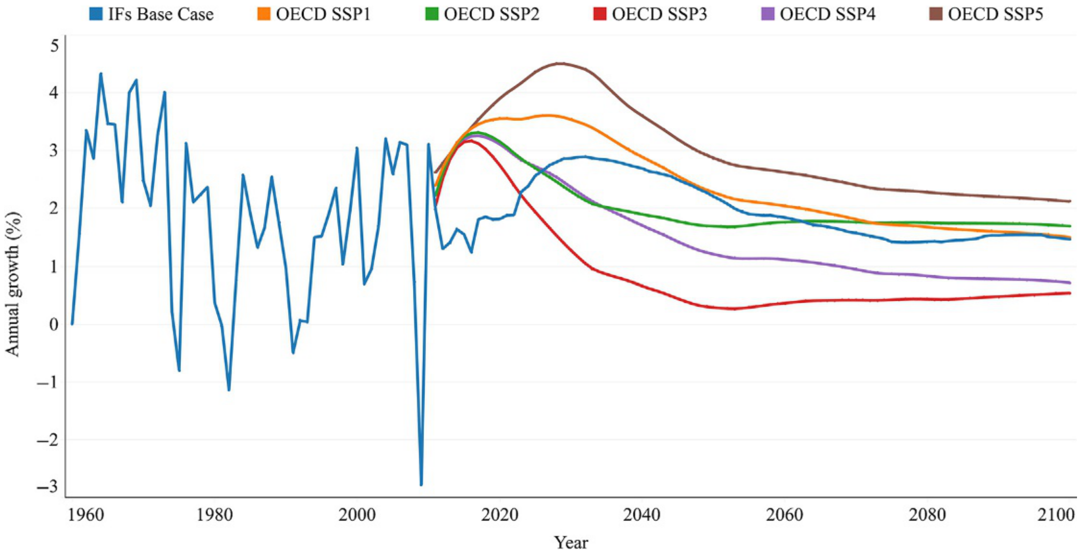

FIG. 6.5 **Global GDP per capita growth rates: History and comparative scenarios to 2100.**
Note: Compares IFs Base Case with Shared Socioeconomic Pathway (SSP) economic scenarios generated by OECD. IFs values through 2022 reflect IMF data and projections. Source: IFs Version 7.36; historical data from the World Bank's World Development Indicators, and OECD projections from SSP database (Version 1.1) hosted by IIASA at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

Across the various SSP scenarios, the global GDP projections for 2100 vary greatly, again considerably more than the factor of 2.25 that separates UNPD high and low population variants. Projections across the SSP scenarios from the OECD vary by a factor of 3.6, and SSP representations from CEPII, using the MaGE model, vary by a factor of 5.0 (Fouré and Fontagné, 2016). Such significant uncertainty around future GDP has very important consequences for alternative projections of other variables explored across this volume.[22]

Turning to poverty, available outlooks mostly focus on the 2030 horizon of the Sustainable Development Goals. Burt et al. (2014) and Milante et al. (2016) did comparative reviews of other studies, including ones by Chandy et al. (2013), Edward and Sumner (2013), and Ravallion (2013). The studies reviewed presented multiple scenarios, and the global numbers in extreme poverty in 2030 ranged from somewhat less than 200 million (which would be 2.3%) to a bit more than 800 million (9.5%), with one outlier near 1.1 billion. A more recent study (Cuaresma et al., 2018, pp. 1–6) projected global values for the five SSP scenarios in 2030 ranging from 4.5% (375 million) to almost 6.0% (506 million), a quite narrow range.

Fig. 6.6 shows the IFs Base Case scenario for the percentage of people living in extreme poverty (defined as less than $1.90 per day in $2011) by country-income category; the global rate in 2030 is near the high end of the other projection sets at 7.6%, declining to 3.9% in 2050.[23]

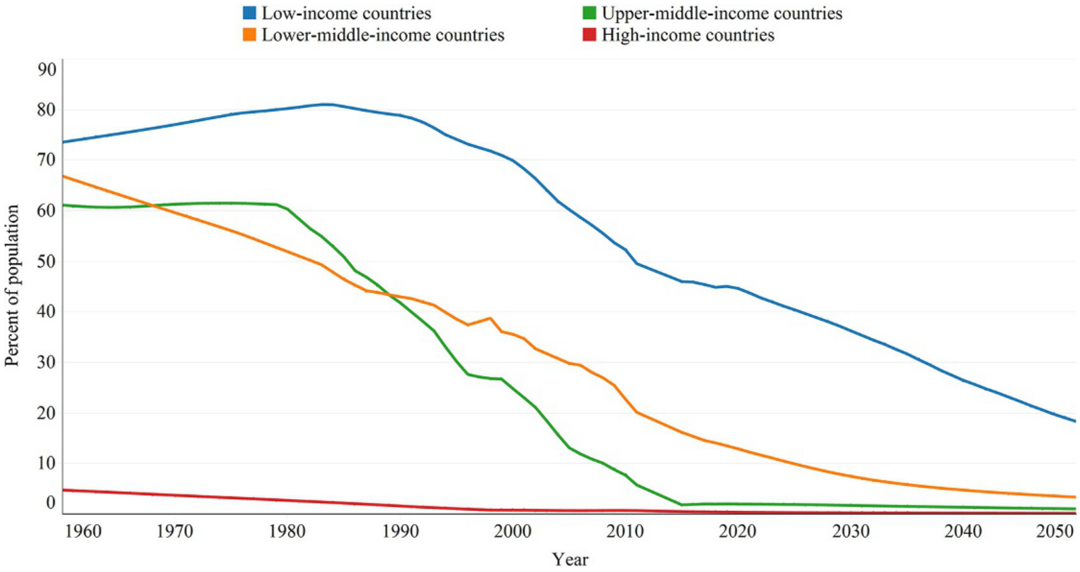

FIG. 6.6 **Poverty rates by country economy classification: History and IFs Base Case scenario to 2050.** *Note: Uses World Bank classifications based on gross national income per capita and poverty level of $1.90 daily in $2011. Source: IFs Version 7.36; historical data from the World Bank's World Development Indicators using interpolation to fill holes and removing 2012–2014 because of incomplete data.*

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[22] Scenario sets often provide quite extreme values, however, so as to avoid omitting possible outcomes. In contrast, the range for GDP in the GEO-4 scenarios built by the IFs project is less than a factor of 2.0.

[23] A major source of variation across projection sets is uncertainty about the current rate for India, where as of this writing there had not been a survey since 2011.

6.2 GOVERNMENT FINANCE

The embedding of economic sector-specific and intersectoral supply and demand accounting within a broader SAM framework provides bridges between modeling of the economy and of governance. Before turning to more specific modeling of governance, this section elaborates that bridging financial substructure of SAMs, focusing on government revenues and expenditures (for more detail than provided here, see Hughes, 2015).

6.2.1 Concepts, Structures, and Data

The basic concepts and structures of government finance—revenues and expenditures with typologies of their components or subtypes— are very simple on the surface. Government collects revenues from a variety of income streams, including household income taxes, firm income/profit taxes, household and firm social security/welfare taxes (including public pension plan contributions), and indirect taxes. Expenditures fall into two general categories and their subcategories: transfer payments (both pensions and social welfare) and direct consumption/public investment expenditures (such as military, infrastructure, and R&D).

Primary government revenue and expenditure data sources include the IMF's Government Finance Statistics, the World Bank's World Development Indicators (mostly built on IMF data), and the OECD, which also provides data on foreign assistance (OECD, 2017a). In addition, the International Centre for Tax and Development (ICTD), with focus on developing countries, especially Africa, has recently been gathering central and total government revenue data from such international organizations and more localized sources (Prichard et al., 2014). If the funding and effort of the ICTD continues, it will prove a very valuable resource.[24]

Given that most government finance data ultimately come from governments (and then are distributed to users via intergovernmental organizations), it may seem ironic that some of the most difficult data to obtain concern government finance. However, there are several reasons for this beyond any inherent tendency for individuals and organizations to hold financial data tightly. A key reason is the complexity of government. For instance, most countries have multiple levels of government, and the degree of financial independence of those levels varies greatly. The interest of the IFs project is primarily in total government finance, but also in the division of central and local sources and uses. Many data are available only at the central government level, which is particularly problematic for federal systems with strong and often independent financing at subsidiary levels. Also, many expenditure targets of government (including those as disparate as infrastructure construction and pensions of the elderly) combine inputs from public and private sources, but data on household and firm spending are often not collected.

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[24] Initially funded in 2010 by a five-year grant from the UK Department for International Development (DFID) and NORAD, ICTD is now funded by DFID and the Bill and Melinda Gates Foundation. See http://www.ictd.ac/.

6.2.2 Government Finance Transitions

More than a century ago, the German economist Adolph Wagner (1835–1917) identified the propensity of governments to gradually increase the share of the economy they collect and use (Wagner, 1892), a pattern that has come to be known as Wagner's law. Consistent with this, the government expenditure share in OECD countries grew from around 10% of GDP in 1870 (World Bank, 1997, p. 2) to a relatively stable 40%–45% between 1991 and 2015 (IFs calculations using IMF data). Non-OECD countries exhibit similar but more recent patterns of growth (see Fig. 6.7). Within the total expenditure picture there are different patterns for direct consumption expenditures (such as those on the military, education, health, and infrastructure) and transfer payments. Global general government direct consumption expenditures (without transfer payments) have climbed since 1960 as a portion of GDP to about 14%–18% (IFs calculations using WDI data). Transfer payments have climbed more rapidly and now exceed direct expenditures globally.

6.2.3 Modeling Government Finance

There is remarkably little longer-term global forecasting of government finance (either of revenues or expenditures). This is surprising, given the central importance of government spending with respect to public goods underlying human development (including education and health) and economic wellbeing (including infrastructure, transfer payments for welfare

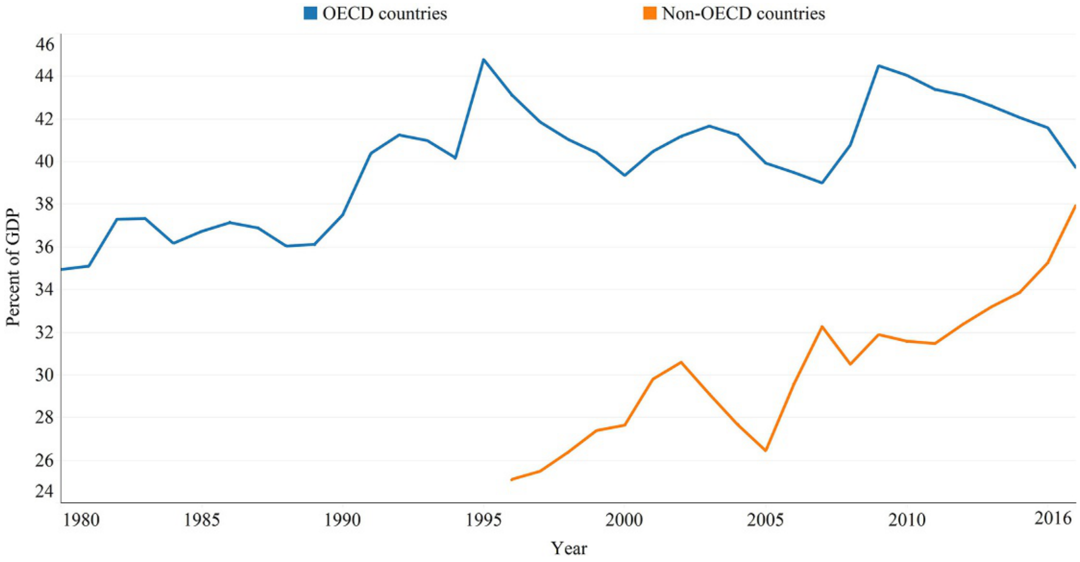

FIG. 6.7 **General government total expenditures as percent of GDP for OECD and non-OECD country groups: History from 1980.**

Note: Uses GDP-weighted averages. Includes direct consumption on goods and services and transfer payments. Source: IFs Version 7.36, using data from the International Monetary Fund's Government Finance Statistics. Few data for non-OECD economies are available before 1996.

and pensions, and research and development). Logically, such forecasting would occur in models that represent a larger social accounting matrix, making it more likely in general equilibrium models than in macroeconomic models.

Because of the SAM database requirements of such general equilibrium models, most of the existing ones discussed in this chapter and in Chapter 3 build on the GTAP database.[25] GTAP supplements its fundamentally important input-output matrices and trade data with data on energy volume, carbon dioxide emissions, other greenhouse gases, migration (including wages and remittances), and land use (Aguiar et al., 2016). In addition to GTAP's focus on import and export duties and subsidies that are obviously relevant to analysis of trade issues, its coverage of government finance includes significant other government revenues; its limitations are primarily on the expenditure side. Thus, most available economic models, including general equilibrium models, also lack extensive government financial coverage.

One model with some substantial treatment of government finance, largely exogenously directed, is the General Equilibrium Model for Economy-Energy-Environment (GEM-E3) system (Capros et al., 2013, p. 56). The GEM-E3 system represents government consumption and transfers on the expenditure side. On the revenue side, it exogenously represents nine sources: indirect taxes, environmental taxes, direct taxes, value added taxes, production subsidies, social security contributions, import duties, foreign transfers, and government firms.[26]

Budgeting is a satisficing activity involving the interaction of many top-down and bottom-up pressures and demands, making it especially challenging for modelers. One of the best efforts to model government finance endogenously was that of Cusack (1987) in the government budgeting submodel of GLOBUS. As Cusack pointed out (1987, p. 338), "There is probably no aspect of the behavior of government for which the unified rational actor model is more inappropriate than in the case of budgeting." The GLOBUS representation of both revenue and expenditure sides was quite similar to, and in fact influenced, that in IFs, including the accumulation of revenue and expenditure imbalances in a stock variable called government debt (GDEBT). The GLOBUS system gave special attention to international politics, and therefore to the relationship of power and threat to military spending. It did not elaborate representation of systems such as education, health, or infrastructure that might drive the demand for expenditure in those categories. One of its unique features was parametric assignment of differential bargaining power to the fiscal authorities and to spending demands from the military, civilian, and capital investment bureaucracies for its 25 countries. Forecasts were limited to 1970 through 2010.

6.2.4 Government Finance in IFs

In the IFs system's conceptual structure for government finance, revenues come from household, firm, and indirect taxes, and expenditures are split between transfer payments (social welfare and pensions) and direct expenditures. The latter are differentiated into

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[25] See https://www.gtap.agecon.purdue.edu/about/data_models.asp for a list of models built on GTAP data.

[26] Capros et al. (2013) do not make clear how any revenue flows might be endogenized for the 38 regions. Forecasts apparently extend to 2050.

military, health, education, R&D, core infrastructure (infrastructure types explicitly represented in the IFs physical model; see Section 7.3.4), other infrastructure, and an overall residual "other" category that includes administrative expenditures.

Government finance data in IFs come primarily from the sources identified earlier: IMF, World Bank, OECD, and ICTD. These sources provide various but incomplete combinations of local, central, and total government revenues and expenditures. The preprocessor of IFs contains algorithmic logic for building as clear and consistent a picture as possible of government revenues and expenditures at the separate levels and in total. It prioritizes use of series and fills holes with cross-sectionally estimated data. Yet the incomplete and inconsistent character of the data remains a key problem.

Modeling government finance requires representing three balancing and allocative processes. At the highest level, the balancing involves total government revenues and total government expenditures. Governments do not balance revenues and expenditures in the short or even medium run, but rather are constrained to limit total debt relative to economy size in the long run. The approach to this balancing in IFs is to compute annual imbalances and to accumulate these in a stock variable that represents net government debt (or assets). That stock variable as a percentage of GDP differs from a target level related to initial values. A PID controller (see the earlier discussion in Section 6.1.4.3) uses the difference, and the annual change in that difference, to provide signals to the revenue and expenditure sides that change them in a process that, like other PID systems in IFs, chases equilibrium across time.

The second balancing process requires reconciliation of the expenditure demand summed across categories with the total expenditures of government in any given year, and therefore calls for algorithmic balancing of top down calculations of expenditures with bottom up pressures for them. The balancing is done separately for direct consumption and transfer payments with the final total expenditure being the sum of the two.

The third and most elaborate process, discussed at some length in Sections 6.2.4.2 and 6.2.4.3, is representing the interaction of demands for direct government spending in individual consumption/investment categories with the total spending allocated by government to such consumption/investment. Like the process around MFP, this balancing process strongly connects the multiple models and issue areas of IFs. For instance, scenario interventions related to government expenditures in any of these areas have impacts on spending in the others and on total government finance.

Levels of taxation and total expenditure, as well as transfers of income to households, clearly have important implications for economies and societies. Flows directed to ends such as education, health, infrastructure, R&D, and defense are investments in public goods. Although the legacy variable names (especially *GOVCON*) in IFs unfortunately suggest that these are consumption expenditures, they are, in fact, often social investment expenditures.

6.2.4.1 Government Consumption/Investment

Both the revenue and expenditure sides are fundamentally important to modeling of government finance, although arguably the ability to mobilize revenues is the more important because it poses an ultimate constraint on expenditures. Yet linkages to other models in the IFs system exist primarily through the expenditure side; those models push demands for spending to government finance, while spending allocations affect developmental outcomes in those models. Thus, the focus in the discussion that follows is on expenditures. For full documentation on IFs, see http://pardee.du.edu/wiki/Understand_the_Model.

As explained previously, IFs divides total government consumption (*GOVCON*) into a set of destination sectors (*GDS*). Modeling the allocation of total *GOVCON* to the sectors involves the determination of destination sector-specific demands for funding, followed by reconciliation of the sum of sector-specific or bottom-up demands with the more top-down total of expenditures (*GOVCON*). An algorithm of importance in the reconciliation involves a normalization process for sectoral demands with *GOVCON* that can give some sectors greater "clout" than others in protecting their demand. Both steps are elaborated here in turn.

6.2.4.2 Sectoral Demand (GDS) Calculations

The generic modeling approach of IFs for spending demand (*GDSDem*) is discussed first, followed by a discussion of sector-specific variations.

Demand for public spending is a percentage (*Gk*) of *GDP* for each destination sector g. It is a function of (1) specialized model values when such models exist in IFs, as with health, education, and infrastructure; less elaborate formulations in other cases; (2) general patterns globally; and (3) historical patterns of spending specific to countries (when data are available). Scenario intervention via a multiplicative parameter (***gdsm***), changed from the default value of 1.0, can force adjustments in spending demand.

$$GDSDem_{r,g,t} = Gk_{r,g,t}/100 * GDP_{r,t} * \boldsymbol{gdsm}_{r,g=mil}$$

where

$$Gk_{r,g,t} = \boldsymbol{gdsbudgetconv}_{r,g,t} * GkModel_{r,g,t} + \left(1 - \boldsymbol{gdsbudgetconv}_{r,g,t}\right) * GkGeneral_{r,g,t}$$

$$GkGeneral_{r,g,t} = Converge\left(GkRI_{r,g,t=1}, 1, 200\right) * GkComp_{r,g,t}$$

$$GkComp_{r,g,t} = AnalFunc(GDPPCP_{r,t})$$

$$GkRI_{r,g,t=1} = \frac{GDS_{r,g,t=1}/GDP_{r,t=1}}{GkComp_{r,g,t=1}}$$

The core of the formulation here is the computation of *Gk*. At the top level, it is a parameter-driven weighted sum (weighted by the parameter ***gdsbudgetconv***) of (1) the value for spending demand as a portion of *GDP* from a specialized model (*GkModel*); and (2) a generalized value (*GkGeneral*) that represents a data-adjusted global pattern of spending rates that change with level of economic development.

The generalized value is rooted in a global pattern (*GkComp*) from a cross-sectionally estimated function that indicates how the share of GDP directed to each sector tends to change with GDP per capita at PPP (*GDPPCP*). However, we normally have data for actual spending (*GDS*) in the first year ($t = 1$). Hence, in the first year the ratio (*GkRI*) of the actual spending as a portion of *GDP* to the value from the estimated function indicates the degree to which each country's value deviates from "expected" rates of spending. *GkRI* is a "shift factor." Recognizing that it represents a variation from the general pattern that tends to erode over time (it may constitute data error or reflect historical path dependencies that temporarily overshoot or undershoot the general pattern), we converge the shift factor to 1 over a very long period (200 years) using the IFs internal convergence function.

MILITARY SECTOR

IFs does not have a full-scale model for military spending with which to average a value from the global function. The model uses an action-reaction formulation that links spending demand of countries to the spending (and therefore power) of other countries and the threat (*THREAT*) that they represent (see Section 6.4 on international politics later in this chapter). IFs brings the result of that calculation into the generic calculation of GDS via a multiplier *GkMul*, all modifiable by the scenario multiplier, ***gdsm***.

$$GDSDem_{r,g=mil} = GDP_r * Gk_{r,g=mil} * GkMul_r * \boldsymbol{gdsm}_{r,g=mil}$$

where

$$GkMul_r = F(THREAT_{r,r=other\ countries})$$

HEALTH SECTOR

The health model in IFs generates spending demand as a portion of GDP (see Section 5.2.4.5). One of the health sector's unique features is the representation of both public and private (not shown here) spending. As in the general function discussed earlier, there is a global function based on initial condition data for many countries. Spending demand as a portion of GDP (Gk) is a blend of these bottom-up (from the specifics of each country in health model) and top-down (from a generalized global pattern with economic development level) calculations. For the health and education equations, funds coming from international financial institutions (XWBFLOWS) are added to the basic calculation.

$$\begin{aligned} GDSDem_{r,g=health,educ} &\\ &= GDP_r * Gk_{r,g=health,educ} \\ &\quad /100 * \boldsymbol{gdsm}_{r,g=health,educ} + XWBFLOWS_{r,g=health,edc} \end{aligned}$$

EDUCATION SECTOR

IFs has an extended model for public education spending (see Section 5.3.4.2), but, unlike the health model, it does not at this time represent private spending. With that exception, the education sector is treated similarly to the health sector (for example, it also includes country-specific patterns tied to enrollment levels, a general global function based on initial condition data for many countries, and the possibility of funds from international organizations provided to governments but targeted for education, with logic like that of health, described earlier).

CORE INFRASTRUCTURE SECTOR

There is an extended model (see Section 7.3.4) that represents both public and private spending for core infrastructure (roads, electricity, water and sanitation, and information and communications technology). There is no general global function for spending in this category because of the scarcity of cross-sectional data, so the model value of spending demand is not averaged with any general global one. Hence the value of *GDSDem* comes completely from a model procedure (*CalcInfraBudgetDemand*) that adds up the public portions of the new construction and maintenance costs for various types of infrastructure, as calculated in the full infrastructure model.[27]

OTHER INFRASTRUCTURE SECTOR

There is no extended model (nor are there historical data) for this residual sector (which would include railroads, airports and seaports), but there is a general stylized global function that estimates the value of spending demand.

RESEARCH AND DEVELOPMENT (R&D)

There is no extended model for this sector. However, there is a process of slow convergence of the initial shift factor (representing initial data) to the generalized function for spending as a function of GDP per capita.

The process of determining public R&D spending is complicated by the model having variables for both public expenditures in *GDS* and a representation of total public and private expenditures on R&D as a percentage of GDP (*RANDEXP*). This is handled by computing private expenditures as a share of GDP in the first year as a residual (*RANDEXPPri*) and holding that private share constant over time.

OTHER PUBLIC SPENDING

In the first model year, spending in this category (which would include expenditures on legislatures and top executive officials not linked to provision of a specific service) is computed as a residual within *GOVCON* of spending in other sectors, and its share of GDP is held constant over time.

EXOGENOUS OVERRIDE

It is possible for the model user to override the demand-side structure for *GDS* by specifying two parameters: ***gdstgtval*** carries a desired expenditure share of *GDP* to direct to any spending sector, and ***gdstgtyr*** specifies the number of years from the initial model year over which demand will move to that target.

6.2.4.3 Reconciling Sector-Specific Demands With Expenditure Availability

The total demand (*GDSDem*) for funds may exceed or fall short of the funds computed by the model to be available, in which case the model needs to (1) adjust the values of *GDS* to be consistent with total consumption/investment spending (*GOVCON*), (2) change *GOVCON*, or (3) some mixture of the two. If the parameter ***govconswing*** = 0 (the Base Case default), *GDS* demands are normalized to *GOVCON*. If ***govconswing*** is greater than 0 and up to 1, then *GOVCON* is recomputed toward or to the sum of *GDS* demands.

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[27] A parameter (***infrafinon***) with a default value of 1 can be set to an alternative value so as to set spending on both core and other infrastructure to 0.

$$GOVCON_r = GOVCON_r * (1 - \boldsymbol{govconswing_r}) + GTOT_r * \boldsymbol{govconswing_r}$$

where

$$GTOT_r = \sum_{g=1}^{G} GDSDem_{r,g}$$

When *GOVCON* is anything less than the sum of *GDSDem*, however, and ***govconswing*** does not boost *GOVCON* fully to that sum, the process of normalizing demands to *GOVCON* will involve reductions of spending below demand levels. It is possible to assign priority to sectoral demands identified by the model user using sector-specific "set asides" that protect some or all of the demand. The extent of set asides is determined by a sector-specific parameter (***gdsbudgetprotec***) that takes on values between 0 and 1; values of 0 protect none of the bottom-up demand value, and values of 1 protect it all. The normalization will then proceed and apply only to sectors not protected fully or on the portions not protected. In the case of education, health, and infrastructure, the full or reduced levels of government spending are then fed back to the elaborated models of those sectors and constitute funding available for use.

6.2.4.4 Other Government Finance

On the expenditure side, transfer payments (*GOVHHTRN*) supplement direct consumption and tend to grow with economic development much more than does consumption. IFs separately represents transfers for pensions and transfers for general welfare (all non-pension transfers, such as unemployment benefits or child welfare payments). In a top-down calculation, total transfers rise (as a share of GDP) with GDP per capita, using a cross-sectionally estimated function. In a bottom-up calculation, pension transfers as a share of GDP rise with GDP per capita and with the share of the retirement age population within the total population, while welfare transfers rise with population and GDP per capita. Exogenously specified values limit both transfers as a share of GDP. Assuming effective social pressures within those limits, the initial calculation of total transfer is the maximum of the top-down and bottom-up calculations. The process of equilibration around government debt (discussed later) may, however, restrain the final calculation of transfer payments, as well as that of direct expenditures.

The basic calculation of revenues from sources such as household income, firm, and indirect taxes involves the use of cross-sectionally estimated functions driven by GDP per capita at PPP. These have an upward slope consistent with Wagner's law. Country tax rates converge to the generic functions over time, converging upward more rapidly than downward.

The calculation of foreign aid receipts requires special attention because the GDPs of donor countries are not growing as rapidly as those of recipient countries are, and because recipient countries might reasonably be expected to progressively outgrow the need for significant levels of assistance. As a function of GDP per capita, the model includes a cross-sectionally estimated pattern of aid receipts as a portion of GDP. That function guides a shift, over time, of available aid to the countries where it is most needed.

6.2.4.5 Balancing Revenues and Expenditures

The government's fiscal balance is revenues, including aid receipts if any, and net flows from the IMF and World Bank (computed in a separate logic) if any, minus expenditures.

Government financial debt or (potentially but seldom) net assets is adjusted by the net expenditures. The portion of foreign aid receipts that consists of grants rather than loans is excluded from that debt adjustment; information in OECD (2017a) helped with our parameterization of grant and loan shares of aid.

Government debt as a portion of GDP must be maintained at reasonable levels to avoid fiscal crisis. Target levels in the real world are difficult to identify. Whereas prices of goods and services equilibrate economic markets and interest rates equilibrate financial markets, there is no clear equilibration variable for government finance, but rather a political process pressed by market acceptance of debt levels. In IFs, target levels reflect the initial debt-to-GDP ratio or ratchet somewhat downward if revenues exceed expenditures (but, to avoid free lunches, not upward with revenue deficits). IFs uses the PID process (see again Section 6.1.4.3) to adjust multipliers on revenues and expenditures upward or downward over time so as to maintain rough equilibrium between revenues and expenditures and, more importantly, reasonable levels of government debt.

6.2.4.6 Limitations

Many of the limitations of the IFs government finance model reflect omissions, often related to inadequacy of available data. For instance, it does not represent government-owned enterprises, not only important in a country like China but also in countries with state-owned energy or other raw material producing enterprises. Nor does IFs represent subsidies to firms, whether state owned or private. Such representations would strengthen the system's ability to represent corruption in the governance model (discussed next in this chapter). With respect to private funding that is related to government finance, IFs fails to represent private spending in education and represents such spending in health rather crudely. Further, the treatment of foreign aid has been hampered by difficulties in distinguishing loan and grant portions by country income level, in part because many loans are ultimately forgiven.

Most significant is the lack of an elaborated treatment of local government finance, including local revenue raising and spending, as well as central-local government transfers. The available database for such specification is inadequate.

6.2.5 Comparative Scenarios

I am aware of no other long-term global scenarios of total government revenues and expenditures, so Fig. 6.8 shows them across the World Bank country income groupings only from the IFs Base Case. There are some important insights from the graphic. First, there is upward movement across both time and income levels of government revenues and expenditures as a percentage of GDP, consistent with Wagner's law (an increase that would result from both increased government abilities to extract revenues and higher demands for public goods, especially transfer payments like pensions and health care). That movement produces some convergence of developing economies to those of high-income countries. Second, there are early-period imbalances between revenues and expenditures that require adjustments if government debt as a portion of GDP is to be kept from continued and unsustainable growth such as that experienced during the Great Recession after 2007. These adjustments will reflect the outcome of interacting upward pressure for revenues and pressure toward restraint for expenditures. Interestingly, in aggregate, the adjustment needs in high-income countries exceed those in developing ones. Because of rapid aging in societies around the world, but

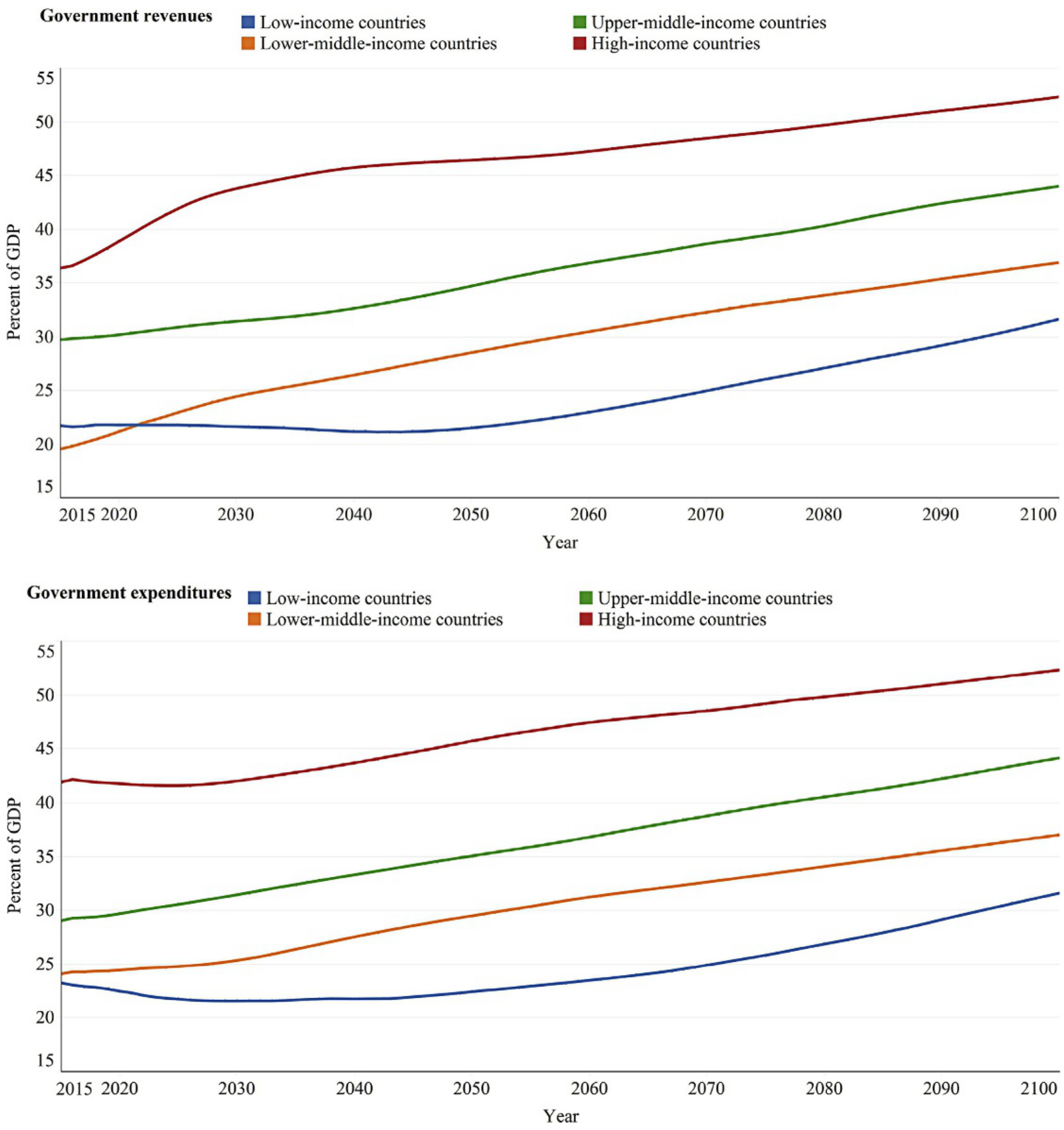

FIG. 6.8 **Government revenues (with foreign aid) and expenditures as percent of GDP by country economy classification: IFs Base Case scenario to 2100.**
Note: Uses World Bank classifications based on gross national income per capita. Both panels show combined central and local government values. Source: IFs Version 7.36, initialized with data from the International Monetary Fund's Government Finance Statistics.

especially in high-income ones, transfer payments will be a major pressure on expenditures (more so than direct government expenditures), and the primary adjustments will likely occur on the revenue side. It is not at all clear that high-income or other countries will find it politically palatable to make the adjustments that Fig. 6.8 suggests will be needed.

A variation on the top panel of Fig. 6.8 that showed only domestic revenues would indicate that low-income countries mobilize a smaller share of GDP than do lower-middle-income countries. Thus a third analytical insight is that low-income countries face a special complication due to high dependence on foreign assistance as a portion of government revenues. Specifically, their economic growth rates are now faster than those of the high-income donor countries, who are unlikely to raise aid donations as a percentage of GDP. Therefore aid receipts in low-income countries will almost certainly fall as shares of GDP and of total revenues across the first half of the century, and those countries will be forced to make a transition to greater dependence on domestic revenues. They may experience relatively stagnant total revenue and expenditure rates for some time as they make that transition, falling behind lower-middle-income countries.

While studies on the future of total government finance may be scarce, there are analyses of some components of it, particularly those under upward pressure, such as the health and pension requirements of an aging population, with which IFs results can be compared. In an OECD study, de la Maisonneuve and Oliveira Martins (2015) forecast that public spending by OECD countries on health and long-term care as a share of GDP would double to nearly 14% by 2060, but with policy action could be held to 9.5%. The IFs Base Case value for the same countries in 2060 for public health spending alone, constrained by financial accounting, is 10.1%. The GBD Health Financing Collaborator Network (2017) forecast global and high-income country public health spending in 2040 to be 5.4% and 8.2% of GDP, respectively. The numbers from the IFs Base Case are somewhat higher at 6.5% and 8.8%. For total public and private health spending, the GBD Network's study anticipates 8.2% and 12.5%, compared to values from IFs of 11.7% and 15.6%. Somewhat surprisingly, given rapid growth in health spending historically, the GBD study's high-income country values change less than 1% from 2014 to 2040, while IFs values rise by 3.5%.

Turning to public pension spending, an OECD study projected that by 2060 the spending of OECD countries would rise to 10.9% of GDP from 8.9% in 2013–2015 (OECD, 2017b, p. 147). That compares to a rise for OECD countries in the IFs Base Case to 11.8% from 7.8% in 2015. IFs initial conditions and growth pattern are more nearly similar to an earlier study by the OECD that projected that by 2050 the spending of major OECD countries would rise 3.4 percentage points above the 7.4% level of 2000 (OECD, 2001, p. 154). IFs shows a 3.3 percentage point rise over that period.

6.3 DOMESTIC GOVERNANCE AND THE SOCIOPOLITICAL SYSTEM

Governance is difficult to conceptualize, much less to measure or forecast. That conceptualization and measurement is a necessary prelude to modeling and exploring possible futures of human interaction.

6.3.1 Concepts, Structures, and Data

Governance is the relationship between government and the broader sociopolitical or, even more broadly, sociocultural system. Three major global transitions unfolding over approximately the last five centuries have shaped governance globally today and help conceptualize it (Hughes et al., 2014; Joshi et al., 2015).

The first major unfolding was a ***security*** *transition* interacting with the creation of the modern state system, generally argued to have begun after the Thirty Years' War in Europe and the Treaty of Westphalia in 1648. The expansion of that state system around the world has involved tremendous violence within and among societies as states struggled to impose order internally and to protect (often also to enrich) themselves externally. The result today is a global system of about 200 sovereign states, most of which are able to offer their citizens the prospect of considerable physical security, but which are also constantly acting to maintain that security while—most of us hope—limiting domestic repression and military expenditure.

Measurements of internal state failure or fragility and of external conflict or war are numerous and fall into two main categories. The first is the extent of violence, generally measured in terms of episode frequency or numbers killed. Data-building efforts have included the Correlates of War Project (see Sarkees and Wayman, 2010, and Small and Singer, 1982); the Uppsala Conflict Data Program (Gleditsch et al., 2002; see also Allansson et al., 2017); the Major Episodes of Political Violence dataset (Marshall, 2016); and the Political Instability Task Force (Goldstone et al., 2010, using a dataset originated by Gurr and extended by Marshall; see also Hewitt et al., 2012 and Marshall et al., 2015).

The second conceptual and data approach to internal security has focused on the drivers of instability risk (as opposed to overt violence) aggregated into indices. Drivers cut across subcategories such as demographic, economic, military, and other social variables, and include (though not necessarily all in any one index) rapid population growth, high poverty, poor service delivery, low economic growth, extensive inequality, human rights abuses, government repression, and historical patterns of violence. Existing indices include the Fragile States Index (Carment et al., 2010); Failed States Index (Fund for Peace, 2012); and the State Fragility Index (Marshall and Cole, 2014); see also Hughes et al., 2011 concerning these and others. Approaches to the propensity for international violence are quite different and will be considered in Section 6.4 of this chapter.

Indices of internal security risk or instability fluctuate considerably less over time than does the extent of violence. A common analogy is of a spark and a gas-filled rag—the timing of the spark that ignites the fire of overt conflict is hard to anticipate, but it is relatively easier to assess how wet the rag is. Not surprisingly, most forecasting is of the latter.

The second major unfolding in governance globally was (and is) a ***capacity*** *transition* involving the creation of governmental competence and effectiveness in providing broader socioeconomic wellbeing. Max Weber (1978; originally 1922) emphasized the development of a system of public administration that supports the goals of the state. Today we understand those goals to be framed heavily by the concept of public goods, those elements of wellbeing that individuals cannot fully provide themselves. In addition to security, public goods include both hard infrastructure and soft infrastructure, such as justice systems, as well as contributions to services, such as education, health, and environmental protection, all of which involve social externalities beyond those that individual action would address.

In operationalizing capacity, we can again usefully conceptualize and measure two subdimensions. Capacity requires resources, hence government revenues. We have already discussed the growth of revenues that has occurred in today's high-income countries and that is occurring now in developing ones. The second subdimension is effective use of such revenues for public purposes. Again there are many measures, including the six of the World Bank's Worldwide Governance Indicators project (Kaufmann et al., 2010) which include Control of Corruption (as well as indicators related to security and inclusion). One of the most important elements in effective use of resource is avoiding high levels of corruption, for which the most frequently used measure is Transparency International's Corruption Perceptions Index (Transparency International, 2016).

Government revenues are, on the surface, a flow (discussed earlier in the context of the social accounting matrix), but they tend not to fluctuate wildly for most countries (with the exception of countries that are producers of raw materials). And, like corruption levels and other indicators of effective use of resources (or lack thereof), they are a manifestation of an underlying stock of governance capacity.

The third transition, still much underway, is around ***inclusion****,* the expansion of roles for, and participation by, the broad populace in matters of the larger society. Obvious manifestations have included expansions of suffrage beyond property holders and men; the protection of ethnic and religious minorities (as well as women, albeit often a majority); and extending potential involvement for all in societal decision-making.

The logic of stock and flow accounting applies to governance implicitly, but tends not to be elaborated explicitly. That is, security, capacity, and inclusion are all inherently stock concepts. Societies build them over time, and they are subject to incremental additions and to depletion or destruction. For example, conflict-afflicted states need time, often decades and generational change, before old wounds heal, new institutions take root, and patterns of behavior change. Similarly, societies with established histories of good governance may suffer disruptions (like world wars for Europe), but can draw on many resources for recovery.

With respect to inclusion, it is useful still again to consider two types of measures, each capturing different elements. The first category consists of macro representations of the openness of governance, and looks especially at the extent of formal democracy. Within this category, the Polity Project founded by Ted Gurr and continued by Monty Marshall provides a measure of democracy globally since 1800 (Marshall et al., 2016); the V-Dem Institute dataset version 8 covers 201 countries from 1789 (on Version 7 see Lührmann et al., 2017),[28] and the Freedom House measures of civil and political liberties date back to 1973 (Puddington and Roylance, 2017).

The second category of inclusion consists of more micro representations focused on specific groups. The Minorities at Risk Project begun by Ted Gurr (Asal and Pate, 2005) is self-descriptive. The Cingranelli-Richards Human Rights Data Project (Cingranelli and Richards, 2010) gives special attention to the rights and societal position of women, as do measures such as the United Nations Development Programme's former Gender Empowerment Measure and the newer Gender Development Index (a sex-specific version of the United Nations Development Programme's Human Development Index). Still again, these measurements are not explicitly stocks or flows, but their tendency for slow change represents deep sociocultural patterns that exhibit stock-like character.

6.3.2 Governance Transitions

Fig. 6.9 uses data from three projects to show the growth of the state system across the last two centuries. During most of that period, interstate conflict like that of World Wars I and II took far more lives than did intrastate conflict.

Fig. 6.9 emphasizes the rapid decolonization of the immediate post–World War II period in Asia and in Africa after 1960. The proliferation of states since that war and the absence of a third violent global war have shifted the primary impact of sociopolitical violence to the domestic side in recent decades. Fig. 6.10, using data from the Political Instability Task Force (PITF), shows the wave of country-year conflict that has characterized the last half century,

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[28] On Version 8, see https://www.v-dem.net/en/data/data-version-8/.

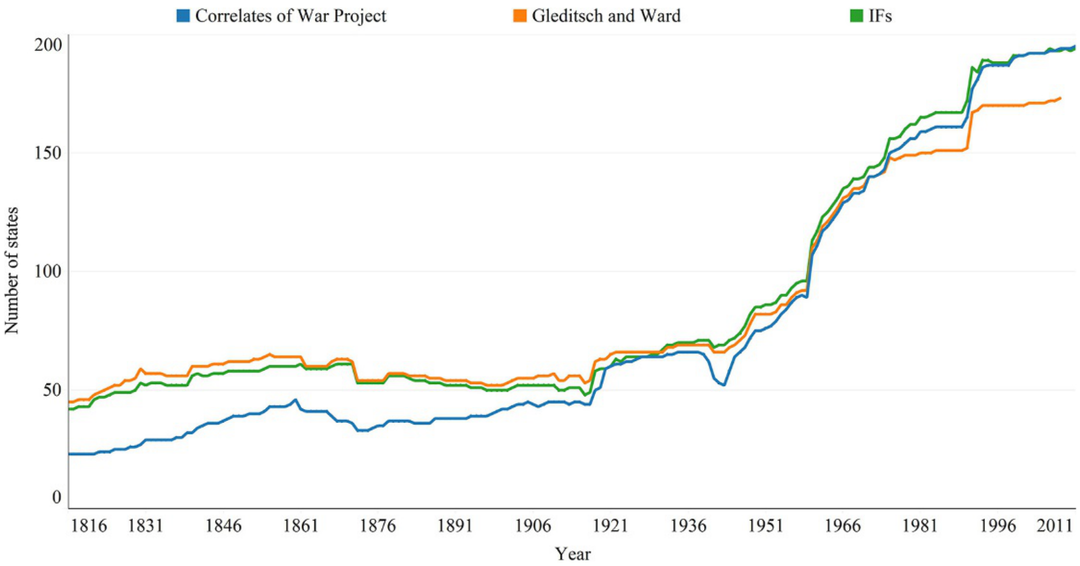

FIG. 6.9 **State system expansion, 1816–2011.**

Note: Although all three projects show a similar trend, they have methodological differences that result in different counts, especially prior to 1920 and after about 1990. Source: IFs project, using data from the Correlates of War Project State System Membership Dataset (v2011); Gleditsch and Ward, 1999 List of Independent States; and the International Futures State List, compiled for Hughes et al., 2014.

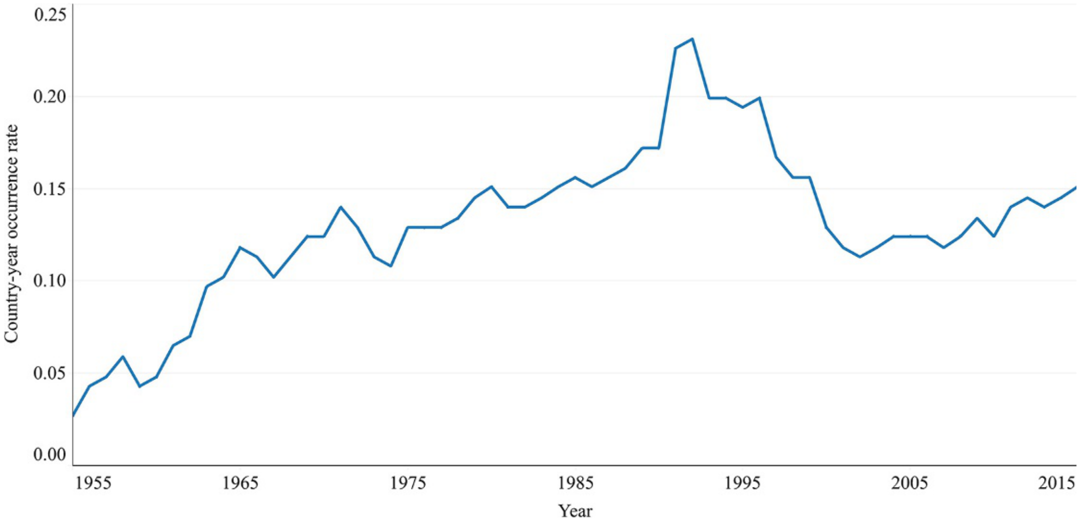

FIG. 6.10 **A wave of intrastate conflict: 1955–2015.**

Note: Values reflect the country-year global average rate of summed initial and continuing events for revolutionary war, ethnic war, genocide/politicide, and adverse regime change (see Marshall et al., 2015 for further description). Source: IFs Version 7.36, using Political Instability Task Force data.

one period of several such waves over the last 200 years (not shown). The peak of this most recent global wave of intrastate conflict came shortly after the end of the Cold War. The growth of conflict leading to that peak is almost certainly a result of both (1) the Cold War itself, with the use by superpowers of proxies in their struggle around the world and (2) the vulnerability of countries in Asia and Africa to conflict after their emergence from colonialism.

Concerning governance capacity, we saw earlier in Figs. 6.7 and 6.8 the transitions that have occurred, and continue to unfold, with respect to government finance. It is much harder to find series that suggest how the effective use of resources, the second component of capacity, has changed. Transparency International (TI) has measured corruption or lack thereof (which is, in part, transparency) since 1995. Although the organization explicitly states that its measurements are inconsistent across time prior to 2012 (Transparency International, 2016, p. 1), the data series on the positive or transparency side rose globally (unweighted average) from 1.3 in 1995 to 3.9 in 2011, suggesting a possible global rise in transparency and, given the 11-point scale, much headroom for improvement.[29] In contrast, however, a transformed TI measure starting in 2012 shows some global increase of corruption in recent years.

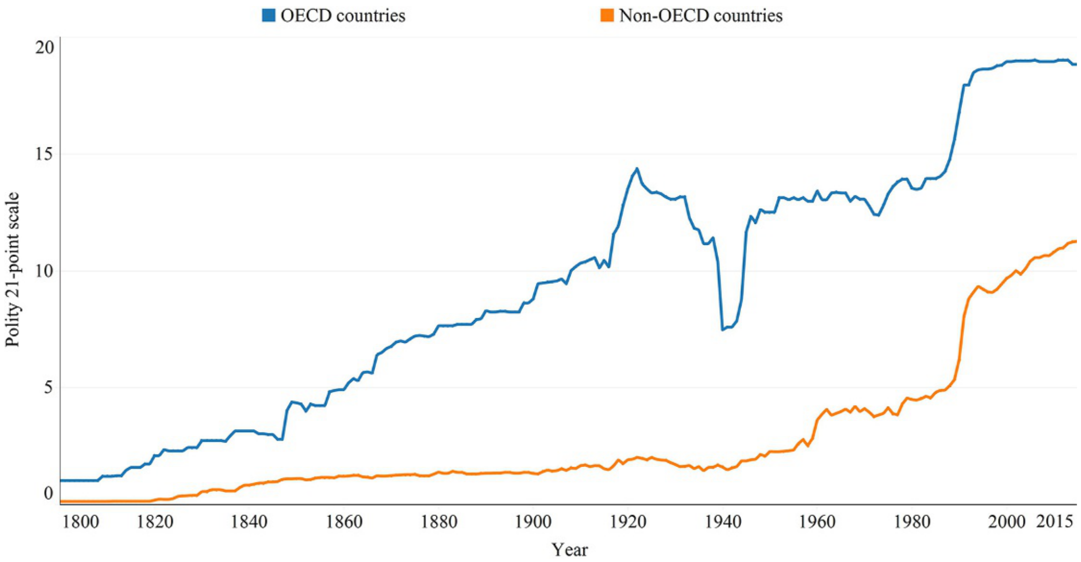

FIG. 6.11 **Democracy and autocracy combined index for OECD and non-OECD countries from 1800–2015.** *Note: Simple country average of Polity Project combined index (democracy minus autocracy plus 10), treating pre-independence geopolitical entities as zeros. A population-weighted average would show a large jump in 1950 when India entered the system. Source: IFs Version 7.36, using Polity Project data hosted by the Center for Systemic Peace at http://www.systemicpeace.org/inscr/inscr.htm.*

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[29] In 2012, Transparency International changed its scaling, making temporal comparison even more difficult. The World Bank corruption measure exists from 1996 to recent years, but is globally renormalized each year, making analysis across time not meaningful.

Turning to the inclusion transition, Fig. 6.11 shows Polity Project data on democracy and autocracy levels since 1800. Here again we can see a wave-like phenomenon that has long been noted in the literature (Huntington, 1991). However, while Huntington described three clear waves of democratization, the portrayal in Fig. 6.11 emphasizes the broadening of advance in the 20th century. The figure includes all current countries across the entire period. Many of those were not independent countries across all of those years and most geopolitical entities were autocracies before independence (either traditional ones or via colonial occupation). Coding them as such in the graphic makes clearer the trend towards democracy globally, albeit lagging in less developed countries, and reduces the relative prominence of global waves (see Hughes and Hillebrand, 2006). We should note, however, that Freedom House measurements indicated that 2017 was the twelfth year of global decline in democracy (Puddington and Roylance, 2017), while the Polity data used for Fig. 6.11 suggest continued advance in non-OECD countries.

Another very important ongoing transition with respect to inclusion, in spite of how far it also is from completion, is political empowerment of women. The V-Dem project index (0–1) of women's empowerment rose globally on a population-weighted basis from 0.30 to 0.70 between 1900 and 2016, with generally comparable rise across all four World Bank country-categories of income.[30]

6.3.3 Modeling of Governance

Despite extensive studies and literatures dealing with the history and current status of these three governance dimensions (security, capacity, and inclusion), there is very limited future-oriented modeling on any of them. This is surprising, in part, because at least some of the general patterns of development in governance (especially the ability to mobilize revenues and to extend inclusion), as well as being subject to more proximate forces, are rooted in deep developmental drivers (such as advance in income and education) that simplify forecasting. It is also surprising because of the important forward linkages that good governance has for the other systems of interest to modelers. For example, this chapter earlier discussed the impacts of social capital on multifactor productivity. In fact, the forward linkages from good governance are extendable to the provision of all public goods, including environmental protection.

Most modeling that does exist has been focused on the security dimension in the short term and especially on fragile or failed states and domestic conflict within them (Hughes et al., 2011). Like much modeling in social science, the work has primarily produced single equations fit to historical data, with limited attention to connecting the equations into a broader and dynamic model of global change.

Hegre et al. (2017) discussed the importance of testing models against both realized (especially out of sample) and unrealized (future) outcomes. In that context, they reviewed three generations of studies of peace and conflict within and among countries, some of which looked to unrealized outcomes. Interestingly, and almost certainly linked to the evolution of global conflict from heavily interstate to predominantly intrastate, the first generation of

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[30] Author's analysis with IFs of data from https://www.v-dem.net/en/data/data-version-7-1/.

studies, in the 1960s and 1970s, was more heavily focused on interstate war than the two more recent ones.

The second generation, dating to the 1980s, moved the focus much more to intrastate conflict. A study by Gurr and Lichbach (1986) reviewed and analyzed theoretical and empirical literature and tested model results against historical data. In addition to emphasizing the importance of conflict persistence (countries in conflict tend to stay in conflict or relapse into it), much of their attention was on the interaction of mobilized discontent within societies and the strength of regimes facing such discontent. Building on work in the context of the GLOBUS project, Eberwein (1987) created a more extensive and dynamic model of domestic political stability (assessed by levels of protest and violence) that looked to the interaction of public satisfaction with state sanctions and repression. Forecasting was limited, however, and focused on a few higher income countries through 2010.

The third generation of studies has directed more attention to forecasting. With the ending of communism and its highly explicit repression, characterizations of regime shifted somewhat, but an at least implicit focus on the interaction of governance capability and the challenges of meeting social expectations remained. Highly influential among third generation studies since the turn of the century, Goldstone et al. (2010) developed a model of instability within the PITF project that fit historical data well, at least prior to recent years that include the Arab Spring. As drivers for conflict, the model found regime type (with partial democracies having fractionalized party systems being especially vulnerable),[31] infant mortality relative to global average, state-led discrimination, and neighboring states in conflict to be most important. The weight given to two variables that are themselves especially hard to forecast (fractionalized partial democracies and state-led discrimination) has contributed to the model's limited use in longer-term publicly available forecasting. Instead, it has been used with very short horizons, mostly within the PITF and the US intelligence community.

Studies in a volume edited by Backer et al. (2017) drew upon a PITF-related system to provide two-year forecasts of the risk of instability and internal conflict (as have Hewitt et al., 2012 and other mostly biennial editions of the Peace and Conflict series).[32] In work that will ultimately support forecasting, Bowlsby et al. (2019) have revisited and enhanced the Goldstone et al. modeling work, finding, for instance, the growing relative importance of demographic size within the broader set of drivers. That might suggest that as intrastate conflict has decreased (see again Fig. 6.10) more of the residual incidence is in large and regionally diverse countries such as Bangladesh, China, India, Nigeria, Pakistan, and Russia.

Although the intelligence community clients of the PITF project undergirding the Goldstone et al. work were primarily interested in anticipating near-term conflict eruption, the global modeling community is significantly interested in forward linkages of conflict over the long term. It matters for development not only whether a new conflict will occur next year in countries like Afghanistan, Egypt, Somalia, or Tunisia, but also whether conflict propensity might persist for one year or several decades. Hegre et al. (2013) literally went much further

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[31] Vreeland (2008) critiqued Polity-based research on a relationship between autocracy and conflict because Polity includes attention to factionalism (related to conflict) in its autocracy characterization.

[32] The Peace and Conflict series is produced in a collaboration of the Graduate Institute, Geneva, and the Center for International Development and Conflict at the University of Maryland.

than most studies by using a model with similarities to that of Goldstone et al. to look out to 2050, distinguishing minor (25–999 deaths) from major (1000+ deaths) conflicts. Hegre and other coauthors (Hegre et al., 2016a) built further on that work to project conflict associated with the five SSP scenarios (see again Section 3.3.2.1) through 2100.

Related to the differences in time horizon for projections and some differences in conceptualization of conflict,[33] there are important differences between the approaches and studies of Goldstone and colleagues and those of Hegre and colleagues with respect to independent variables. Hegre and co-authors have found that conflict is best predicted by a history of conflict, conflict in neighbors, population size, youth bulge, infant mortality, and education attainment level. Hegre et al. (2016a) also added time as a variable related to the state formation process. Because some of the drivers on which Hegre and colleagues have chosen to focus, such as population and education, are among variables in the IIASA database of long-term projections for the SSP scenarios, the project has been able to use that database for historical analysis and as drivers for its own projections.

There is, of course, another possible driver of conflict with special interest for integrated, long-term scenario analysis—namely, climate change. Burke et al. (2009) argued that climate change could raise conflict incidence in Africa by 54% in 2030. Busby et al. (2013), without making specific temporal forecasts, prepared maps showing Africa's vulnerability to climate change and sociopolitical insecurity in interaction with variables such as population density and income level.

Moving from the security to the capacity dimension of governance, the ability to raise and effectively use revenues has drawn some forecasting attention within economic models with SAM structures. For instance, the GEM-E3 model, introduced in earlier discussion in Section 6.2.3, represents a wide range of revenue sources. Analysis with GEM-E3 is, however, focused on the broader implications of exogenously changing the revenue sources or amounts raised rather than on anticipating likely future revenue patterns (Barrios et al., 2013). I am unaware, in fact, of any effort other than that within IFs to build longer-term projections of revenue levels and patterns, or to anticipate corruption or other variables shaping effective use of those revenues.[34]

Turning to the dimension of inclusion, foresight efforts have been limited. Existing modeling focuses overwhelmingly on the future of democracy. For example, Bueno de Mesquita (2002) used a game theory approach in looking at global expansion of democracy to 2028. Cincotta and Doces (2011) built dynamic structures of the ties of demography to democratization, finding that when societies reach a median population age of 28.9 or more they have a 50% chance of being a liberal democracy (Tunisia hit that age marker in 2010, a year before the Arab Spring).[35] A so-far largely missed opportunity for social science is the forecasting of

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[33] Another difference between the projects is that Goldstone et al. (2010) focused on the onset of conflicts, while Hegre et al. (2013) and Hegre et al. (2016a) looked at incidence of conflict, whether onset or continuation.

[34] The IMF's *World Economic Outlook* series provides projections of change in key fiscal variables about five years into the future. For example, see https://www.imf.org/en/Publications/WEO/Issues/2017/09/19/world-economic-outlook-october-2017. Trading Economics uses historical series to forecast such variables across relatively nearly term horizons. See https://tradingeconomics.com/about-te.aspx.

[35] See Cincotta's analysis at https://www.newsecuritybeat.org/2015/05/tunisias-democracy-survive-view-political-demography/.

cultural change and its broader impacts, including democratization. Within the World Values Survey project, Inglehart and Welzel (2005) have provided considerable data and conceptual/theoretical foundation for such modeling, a line of thought that Welzel (2013) has drawn out further with his work on emancipative values, and one that the IFs project began to follow at one time and should pick up again.

6.3.4 Governance in IFs

The three-dimension conceptual framework presented previously (security, capacity, and inclusion) structures the representation of governance in IFs. IFs differentiates two subdimensions for each of the three concepts and computes aggregate indices for each. Causal logic based heavily on regression analysis underpins the model, as if governance variables were flows, even though earlier discussion argued that governance has a stock-like character that might suggest treatment of flows that increment and decrement it.

All three governance dimensions, and the different measures of each, are important variables in IFs. Even so, security stands out, both because success in the security transition is foundational to lasting success in capacity and inclusion transitions and because of its other important forward linkages, as exemplified in the discussion in Section 6.1.4.1 of its impact on social capital and therefore MFP.

6.3.4.1 Security and Internal War

The focus of the discussion here on security and internal war is on IFs formulation of a variable called state failure/internal war (*SFINTLWAR*). The dataset behind its initialization—namely the revolutionary war, ethnic war, and genocide or politicide categories of the Political Instability Task Force[36]—represents internal war in terms of both annual occurrences (yes or no) and a violence magnitude scale. Although IFs includes variables representing both, our key variable is occurrence rather than magnitude. However, we do not represent future occurrence as a binary (yes or no) variable because it would be folly to think that we can anticipate whether there will be internal war in any specific country in any individual year. Instead, we initialize the IFs internal war variable in terms of probability of conflict in each country-year based on recent historical frequency of that country's conflict in the PITF database. We model change in that probability based on driving variables in IFs that also are continuous rather than dichotomous. See Section 6.4 on international war for more of the rationale behind the IFs probabilistic approach; see also Gartzke, 1999). This makes the long-term forecasting approach of IFs more like that of Hegre et al. (2013) than the short-term approach of Goldstone et al. (2010).

To determine the variables in our formulations, however, we gave special attention to the work of the PITF (Esty et al., 1999; Goldstone et al., 2010) as it uses the same dataset on domestic conflict as we do. But we also looked widely at other literature, including that of the Peace Research Institute Oslo (PRIO). There are many relationships in the literature that do not lend themselves to simple statistical analysis or analytical representation—for instance, those that have threshold or ceiling effects. Although we statistically estimated the impact of some driving variables (such as infant mortality and trade openness), we represented many others algorithmically, building on a combination of theoretical and empirical work of others,

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[36] Ted Robert Gurr recommended to us the collapsing of the three categories into the internal war variable.

but also adjusting the algorithms as we undertook extensive analysis of the historical performance of our formulations (Hughes et al., 2014). The variables used generally fall into four groups, presented here.

Persistence and spread of conflict. The literature is very clear that conflict at home begets further conflict at home. Our own historical analysis found a 60% carryover in a moving average of past within-country conflict levels to current ones (*SFINTLWARMA*).

Based on literature and analysis, we also found it important to add a regional contagion effect. Courtesy of data provided by Paul Diehl (then a professor at the University of Illinois), we combined three of the Correlates of War distance categories (contiguous, less than 12 miles separation, and 12–24 miles separation) and added 0.1 to conflict probability for a country for each neighbor with computed conflict probability of its own above 0.2. Because of conflict carryover across time, this algorithm can lead to a positive feedback loop of neighborhood contagion.

Government regime. We looked at regime type, using the Polity measure to consider the relationship of autocracy, democracy, and anocracy (the in-between condition) with conflict (*POLITYDEMOC*). Consistent with studies that have found anocracy rather than autocracy more often related to conflict, our analysis showed the relationship of measures of regime type with conflict to have an inverted U-shaped character, with anocracy at the peak of the inverted U. We created that relationship algorithmically.

Performance of government and social wellbeing. Normed infant mortality (*INFMOR*) proved statistically important as an indicator of the likelihood of internal conflict. Interestingly, in line with findings from the PITF project, this proved to be the best representation for us of a long-term developmental variable (a distal driver) related to security or lack thereof (better than GDP per capita or education level). In essence, it serves as both a distal driver of development and a measure of current performance.

Downturns in economic growth rates (see Collier and Hoeffler, 2004, p. 582 on their impact) preceded the collapse of communism in Europe and Central Asia, the rise of internal conflict in both Latin America and the Middle East in the 1980s, and more recently the events of the Arab Spring. Analysis of the magnitude of downturn required to generate conflict and of the lag between downturn and conflict is complex. Through experimentation directed at fitting historical conflict patterns (running IFs against historical patterns since 1960), we found that a 1% drop in a moving average of economic growth (GDPRMA, carrying 60% of the moving average forward) is associated with a 0.04 point increase on a 0–1 scale for the rate of internal war.

Broader socio-economic conditions. Youth bulges (a high ratio of 15- to 29-year-olds relative to the larger adult population) are a consistently identified driver of domestic instability or conflict (*YTHBULGE*); Urdal (2006) found this relationship to be robust. IFs includes an algorithmic representation of the relationship of youth bulge and conflict. It would have been possible to use median age rather than size of youth bulge. In a review of age-structural theory, Cincotta (2018) reported on analysis showing that as median age of a population climbs from 15 to 45 years, the probability of intrastate conflict declines about 0.4 to near zero.

With respect to the above drivers of conflict, we found that $18,000 per capita (in $2005 at PPP) is a point above which economic downturns and youth bulges tend not to increase the

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[37] This volume has often emphasized the extent to which GDP per capita and education attainment correlate and therefore can be substitutable as drivers of other variables. Thyne (2006) found clear and often strong relationships between reduction in civil war onset and spending on education, education enrollment rates, and literacy.

probability of internal war.[37] We greatly dampened the effects of both of those variables above this level of GDP per capita.

Trade openness (*TRADEOPEN*), the sum of exports (X) and imports (M) over *GDP*, can pick-up a generalized sociopolitical resilience. IFs includes a small downward impact of it on conflict.

The basic formulation in IFs thus includes some statistically specific terms and a number of algorithmic specifications.

$$\begin{aligned} SFINTLWAR_{r,t} = & ((0.1420 + 0.0012 * INFMOR_{r,t} - 0.0006 * TRADEOPEN_{r,t}) \\ & + F(POLITYDEMOC_{r,t}, YTHBULGE_{r,t}, GDPMA_{r,t}, \\ & SFINTLWARMA_{r,t})) * \boldsymbol{sfintlwarm}_{r,t} \end{aligned}$$

where

$$TRADEOPEN_{r,t} = (X_{r,t} + M_{r,t}) / GDP_{r,t}$$

It is common practice in evaluating the performance of models to use historical data for independent variables. Further, when a dependent variable is dependent in part on its values in previous years (as is conflict), it is common in historical fit analysis to use historical values rather than model forecasts for past years. In long-term future analysis, neither of these aides is available, and all must be endogenous. Therefore we initialized our historical testing in 1960 and let IFs run without intervention/adjustment to 2010. We found that, statistically, the domestic conflict probability correlated at the region level with dichotomous data across 1960–2010 at only a 0.19 R-squared level.

We therefore explored the bases of the historical patterns further, and concluded that additional factors were missing. One was the totalitarian repression that lowered conflict in developing Europe and Central Asia until about the time of General Secretary Mikhail Gorbachev (the repression factor in the Eberwein, 1987 model). We added a repression parameter for exogenous manipulation. As a corollary, and perhaps more controversial, we also found it useful to extend the suppression of conflict to sub-Saharan Africa in the middle period of the historical run; our underlying assumption was that the domestic prestige and power of liberation movement leaders, backed by their domestic and superpower supporters, helped dampen the impact of poor underlying conditions.

A second and very important type of factor missing in our basic model was external interventions, such as those of the United States in Southeast Asia in the 1960s and those of the former USSR, and then the United States, in South Asia after 1980. In fact, it is surprising that the best-known and well received studies of historical instability have not identified external interventions as a critical variable. We added a second exogenous parameter to represent such interventions, and then subjectively scaled the repression and intervention parameters for historical analysis. It was (and is) impossible to build such historically unique phenomena into forecasting as in the IFs Base Case, but this historical model testing points to important exogenous parameters for scenario analysis.

With a much better country-year match to actual history (the adjusted R-squared rose to 0.61), our revised historical forecast produced some remarkable similarities to data, including the initially high level of conflict in East Asia and the Pacific and a relatively high rate for South Asia in recent decades. The major problems that remained in our historical forecast included the generation by the model of too much conflict for Latin America and the Caribbean in the 1980s (when economic and social conditions in that region deteriorated significantly) and underestimation of the relatively high levels of conflict in sub-Saharan Africa beyond the end of the Cold War.

In our effort to forecast six different governance variables distributed across the three dimensions, this internal war representation proved to be the most complex. In addition, because of the need to add exogenous representation of repression and external intervention to accomplish good historical fit, it also becomes one in which we can have only limited forecasting confidence. Scenario analysis will always be important in governance, and especially in security forecasting.

6.3.4.2 Other IFs Variables Related to the Three Dimensions

While the likelihood of conflict (whether expressed as a probability or even as a precise prediction of conflict onset) is an important variable, many fragility, state failure, or risk indices represent the security dimension more generally by ranking or scoring countries. Such indices are often a weighted or unweighted average of demographic, social, and economic variables that potentially help differentiate more and less conflict-prone countries. IFs includes a similar risk measure based on a wide range of variables across the model.

With respect to governance capacity, the ability to mobilize revenues and to use them without corruption are key variables. A previous section of this chapter explained the forecasting of revenues. In IFs, corruption is a function of (a) GDP per capita at PPP (inversely related), (b) the dependence of the economy on energy exports (a key element of the resource curse that affects both exchange rates and corruption), and (c) the two inclusion variables in IFs, namely democracy level and gender empowerment of women (again inversely related).

Concerning inclusion, as noted earlier, IFs looks to democracy and gender empowerment. For democracy, we found (like Cincotta and Doces, 2011) that the deeper or distal factor that most directly explains its level is demographic—namely, the magnitude of the youth bulge (the population 15–29 years of age as a share of the 15-and-older population). Other drivers are energy export dependence and gender empowerment. Temporal variation in gender empowerment itself depends heavily on three deeper or distal variables: namely, GDP per capita at PPP, years of education attainment for women 15 years and older, and the youth bulge. This unusual causal structure underlying gender empowerment, involving so many deep drivers, suggests the ties of gender roles to culture and its own slow change (initial conditions obviously also represent the path dependence of cultural patterns).

6.3.4.3 A Deeper Look at Culture

More fully understanding societies requires going below their governance and social conditions in order to look at their value and cultural foundations. IFs computes change in three cultural dimensions identified by the World Values Survey (Inglehart, 1997; Inglehart and Welzel, 2005). The dimensions are survival/self-expression, traditional/secular-rational values, and an integrating materialism/post-materialism dimension. Inglehart identified large cultural regions that have substantially different patterns on these value dimensions, and IFs represents those regions.

Levels on the three cultural dimensions are forecast not only for the country/regional populations as a whole but also for multiple age cohorts within them. Fig. 6.12 shows the rather dramatic variations that we can see by age cohorts both within and across country

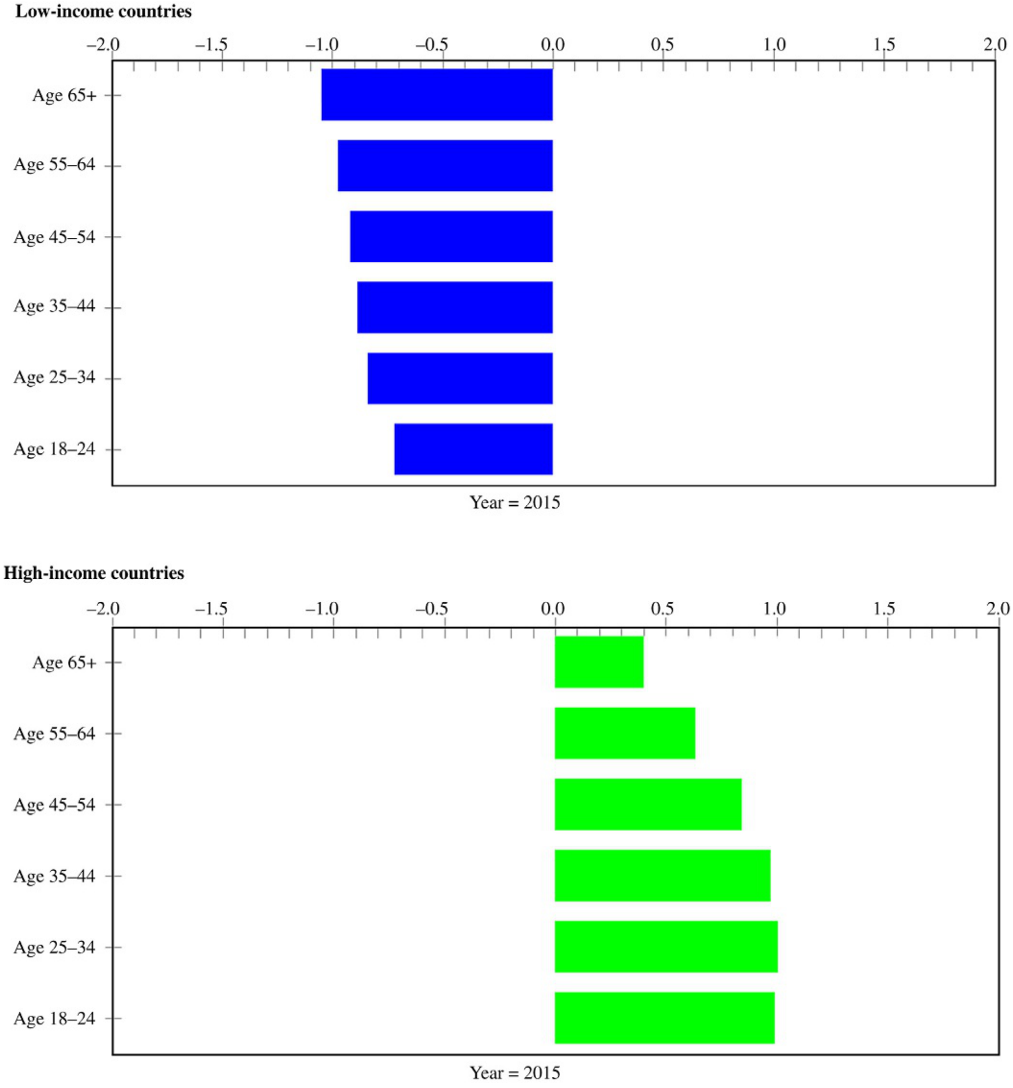

FIG. 6.12 **Index of survival versus self-expression values by age in low- and high-income countries in 2015.** *Note: Uses World Bank low- and high-income country groups. See Inglehart and Welzel, 2005 for description of survival vs. self-expression orientations. Numerical values below zero indicate predominantly survival orientations and those above zero point to greater self-expression. Source: IFs Version 7.36 estimate, initialized using data from the World Values Survey (waves 1–6); wave 6 surveys were completed in 2014.*

groupings by income level. The top panel portrays the considerably greater emphasis that people in low-income countries place on survival values compared to citizens of high-income countries (in the lower panel), where the focus increasingly shifts to self-expression. Within the two country groupings, younger age cohorts, born into better circumstances around most of the world than were their parents and grandparents, are generally more focused on self-expression than their elders are.

Although we have explored the forward linkages of value change to other variables, including democracy, the IFs project has given neither the forecasting of value/culture change nor its impacts the attention they deserve. This area is a great opportunity for creative thinking and modeling in the future.

6.3.4.4 Limitations

Data-building projects foundational to governance are often so tied to specific researchers that they are subject to disruption when project leadership changes. Also, there are significant subjective evaluations required in many of these data-making efforts, not least the specification of democracy level. Those issues put both quality of data and continuity of IFs modeling updates and extensions at some risk.

While this discussion has emphasized that governance has a stock character, the earlier portrayals of historical patterns and transitions, especially that around domestic conflict, make clear also the country-year volatility. The broad global progression toward greater levels of democracy conceals remarkable volatility there, too. In short, governance variables are exceptionally difficult to forecast. The use in IFs of a probabilistic representation of intrastate conflict helps somewhat with indicating country-years in which sudden changes are more or less likely to occur, but the probabilities themselves will generally change slowly and smoothly across time.

Perhaps most important with respect to the broader purposes of this volume, the treatment of governance in IFs is at a high level of aggregation that does not lead easily to endogenous representation of specific policies in many of the issue areas of global modeling. Theoretically, improved governance should make it easier for countries to address a wide range of issues. For some of these that require expenditures, such as support for health, education, and infrastructure, the representation of enhanced revenue raising and spending capacity in IFs does, in fact, allow us to connect endogenously to the issue. The same is true with respect to the issue of income redistribution, although the representation of only two household types limits policy analysis there. But in issue arenas where action typically involves regulation, such as climate change and other environmental issues, the structure of governance in IFs offers limited capacity for specific policy representation. Chapter 9 returns to the difficulty of making highly specific policy recommendations with global models in the context of scenario analysis.

6.3.5 Comparative Scenarios

The work of Hegre and co-authors (e.g., Hegre et al., 2013, 2016a), has produced the only long-term scenario analyses of the domestic security dimension of governance, other than those from IFs, of which I am aware. The formulation of Hegre and the broader team associated with the Uppsala Conflict Data Program (UCDP) has many parallels to IFs, although their independent variable set does not fully match with that of IFs. It includes population size (not in the IFs formulation), infant mortality, demographic composition, neighborhood characteristics, and education levels (IFs uses GDP per capita as an alternative but highly correlated distal driver). Their forecast of domestic conflict in Hegre et al. (2013, p. 261) showed a slowly downward sloping global probability through 2050, very much like that of the IFs Base Case scenario and like the SSP2 implementations (discussed later) shown in both panels of Fig. 6.13.

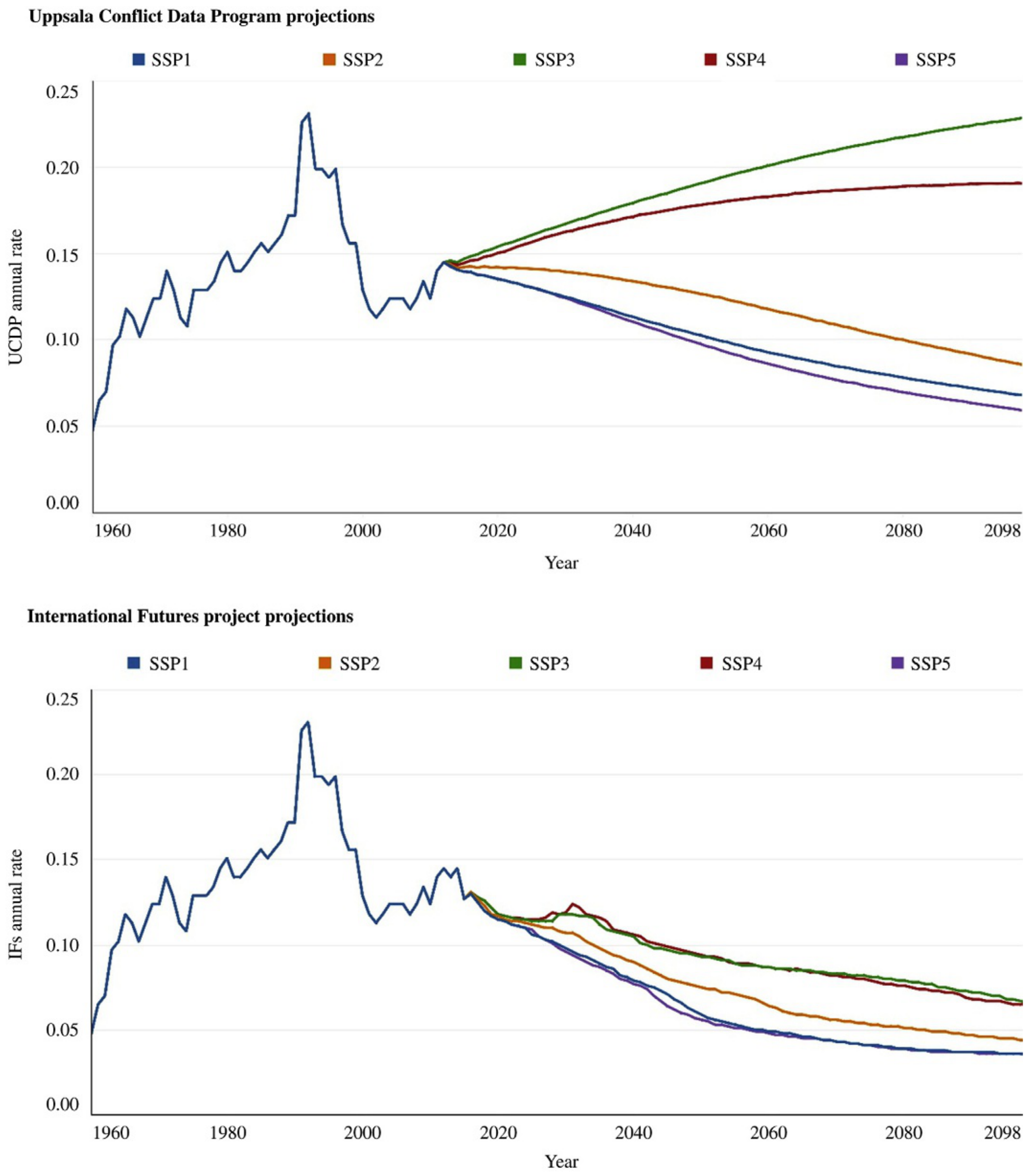

FIG. 6.13 **Internal conflict rate: History and comparative SSP projections to 2098.**
Note: The root institution for the work in the top panel is the Uppsala Conflict Data Program at Uppsala University. The bottom panel was generated by the IFs system. Source: Projections in the top panel replicate Figure 3a (p. 5) in Hegre, H., Buhaug, H., Calvin, K.C., Nordkvelle, J., Waldhoff, S.T., Gilmore, E., 2016. Forecasting civil conflict along the shared socioeconomic pathways. Environ. Res. Lett. 11(5). DOI:10.1088/1748-9326/11/5/054002 (available through CC BY 3.0 license), with values through 2098 generously provided by the authors. Bottom panel is from IFs Version 7.36, with SSPs replicated in IFs by exogenously introducing demographic variables, GDP growth, and adult education attainment from sources described in "Supplementary Note for the SSP Data Set" at https://tntcat.iiasa.ac.at/SspDb/static/download/ssp_suplementary%20text.pdf, and with income distribution assumptions in IFs tied to van der Mensbrugghe (n.d.). Both panels use Political Instability Task Force data until the respective model base years of 2013 (top panel) and 2015 (bottom panel).

Turning to more recent work, Fig. 6.13 shows projections from both the UCDP and the IFs projects of rate of intrastate conflict across each project's implementation of all SSP scenarios. The top panel shows the work of Hegre et al. (2016a) in creating versions of the SSP scenarios from the scenario story lines using projections of driving variables gathered from many sources. The bottom panel shows the results of building the SSPs into IFs exogenously, using elements of the SSP projections from various sources discussed throughout this volume, specifically with GDP from the OECD, population and adult education attainment from WIC/IIASA (also fertility rate, births, and deaths), urban population from the National Center for Atmospheric Research, and Gini from GTAP. IFs then produces the probability of conflict endogenously. Although the future conflict patterns for the middle-of-the-road SSP2 projection are comparable across the UCDP and IFs projects, and trajectories of SSP1 and SSP5 do not differ significantly within or across projects, the projected conflict patterns associated with SSP3 and SSP4 (both with high adaptation challenges) are sharply higher in the UCDP forecasts than in IFs. More direct comparison of driving variables and formulations would be needed in order to understand the reasons for the differences.

Moving beyond conflict to regime types, Hegre et al. (2016b) have produced a scenario that also can be compared with a forecast from IFs. Using the same Polity Project-based series as the IFs project does, Hegre et al. anticipate that nondemocratic regimes will decline from 40% of the global total in 2013 to 18%–20% by 2060. The IFs Base Case anticipates a similarly optimistic decline from 59% to 26% between 2015 and 2060. The initial percentages differ because Hegre, Nygård, et al. consider 167 countries rather than the 186 of IFs, and the countries not treated are more likely to be very poor and nondemocratic.

6.4 INTERNATIONAL/GLOBAL POLITICS

The contemporary global state system has taken shape over the last four centuries. Changes occur constantly in that system, earlier significantly in the membership itself, now primarily in the relative power of states and in the patterns of their relationship. Those relationships involve cooperation and conflict, both of which have great implications for the unfolding of global futures across all of the other issues that this volume considers. Because of its dangers, the threat of military conflict receives a disproportionate amount of attention in international politics, and it will here also.

The IFs project has long sought to forecast changing power of states and to say something about the consequences of those changes for the threat of conflict (see Hughes, 2014). On the cooperative side, data building efforts of the Pardee Center's Diplometrics project,[38] discussed later, increasingly map the extension of interstate connections. Those data will lay the foundations for modeling changing cooperation as well as conflict in the global system.

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[38] See http://www.pardee.du.edu/diplometrics. Jonathan Moyer is leading the extension of the IFs project beyond its initial focus on fairly simple measurement of power and the more complex, but still limited, representation of the drivers of conflict presented here.

6.4.1 Concepts, Structures, and Data

Although competing perspectives or worldviews are important in all issue areas, they take on special significance in thought about international politics (Hughes, 1997). Realism focuses attention on relative state power and its role in shaping interstate relationships, including the pursuit of security and the use of conflict in a fundamentally anarchic environment (Morgenthau, 1973; Waltz, 1979). Liberalism highlights also other state interests, such as mutually beneficial economic exchange and providing public goods (like avoidance of global warming); it also draws attention to cooperative patterns of interaction, including the creation of institutional structures. One conceptual manifestation of liberalism is the notion of complex interdependence among state and non-state actors globally (Keohane and Nye Jr, 1987). Many other perspectives shape thinking, including constructivism with its focus on the influence of ideas and culture, but realism and liberalism have had special prominence.

Power is the central concept in realism, and a common definition is the ability of A to get B to do X (Dahl, 1957, p. 202). Although this is a dyadic concept, most measurement has been monadic, focused on each state's power as represented by its general capabilities. Foundational to much analysis of global power is the Correlates of War (COW) Project (see Ray, 1990; Ray and Singer, 1973; Singer et al., 1972) which measured power as an equally-weighted index of each state's demographic, economic (notably, industrial production), and military capabilities (often proxied by spending). Although the IFs project has been attentive to that tradition, it is outdated in at least three ways. First, technology has moved the strength of economies beyond industrial bases and is itself an important element of power. Second, and related, nuclear capabilities have transformed military power in ways that military spending cannot capture. Third, an attentiveness to soft power (Nye Jr., 2004), more rooted in diplomatic and cultural variables, increasingly supplements the earlier conceptualization and measurement only of material capabilities.

Because state power plays such a central role in almost all analyses of the global political system (Waltz, 2000), and because there is no objective standard against which to assess power measurement, IFs computes three alternative monadic power indices. For many years the IFs project has used an unpublished measure proposed by Evan Hillebrand with input from Paul Herman; the Hillebrand-Herman power index uses GDP per capita as a proxy to add technological capability as a fourth element to the COW mix, and it weights demographics less heavily. Second, Moyer developed a further extension (the Hillebrand-Herman-Moyer index) by adding nuclear capabilities and by adding international interaction-based influence related to embassies abroad, membership in intergovernmental organizations, and involvement in treaties. Third, a global power index (GPI), proposed by Tim Smith, incorporates an even broader range of variables representing material and technological elements of power (including human capital, energy production, and spending on research and development), as well as some international interaction elements (notably trade, foreign aid, and inflows of foreign direct investment). The IFs project also has created a dyadic measure called foreign bilateral influence capacity (FBIC index) that looks at trade, trade agreements, arms transfers, military alliances, diplomatic representation, shared intergovernmental organization (IGO) membership, and foreign aid. See Moyer et al. (2017) for elaboration of the FBIC.

Although the IFs project uses existing data series in almost all areas of its modeling, the growing attention in international political assessment to patterns of state interactions (both cooperative and conflictual) and the character and role of non-state actors in the changing global system has outstripped the data available. The Diplometrics project at the Pardee Center has updated a variety of databases and developed totally new ones. These include diplomatic representation, interstate visits of heads of state, adherence to treaties, membership in intergovernmental organizations, and the size and character of nongovernmental organizations. Further, the Pardee Center has developed a data analysis tool called the data aggregator (DataGator) that facilitates both transformations of data and work across what have often earlier been incompatible databases due to factors such as differing country names, coverage, and time representation.[39]

These data and conceptual efforts are building the foundation not just for the forecasting of power and conflict within the realist tradition, but also of the international interconnections to which liberals draw our attention. Ultimately, these efforts may also allow the IFs project to create an index of global governance.

Turning to the important concept of conflict, the IFs project conceptualizes interstate threat in terms of probability of conflict within a pair of countries (a dyad). If one were to conceptualize threat in terms of the damage that one country could do another, the threat term would be directional or asymmetric like the measure of influence—Russia, for example, can do more damage to the Ukraine than the reverse. Our currently operationalized conceptualization focuses on the threat of dyadic conflict, however, and it is therefore symmetric—both countries of a dyad will either be in conflict or not.

There are several sources of data on interstate conflict. The COW project (Sarkees and Wayman, 2010; Small and Singer, 1982) created a very widely used and historically long series on wars. PRIO and UCDP have generated multiple but shorter intrastate and interstate conflict series with a lower threshold for conflict definition than COW; in collaboration with UCDP, PRIO built a 1946–1988 series and UCDP has done subsequent updating (Allansson et al., 2017; Gleditsch et al., 2002).

Some datasets have also emerged from analysis of events that may or may not result in deaths, such as that in the Conflict and Peace Data Bank (COPDAB) project of Azar (1980) and the Kansas Event Data System (KEDS) project of Schrodt et al. (1994). Events data often have more temporal detail than the country-year basis of most conflict datasets. For instance, Zeev Maoz, who became director of the COW project in 2013, has built the dyadic Militarized Interstate Disputes (MID) dataset with coverage from 1816 through 2010 (in version 4.2). MID data track the days and intensity of militarized interstate disputes, defined in that project as threats, displays, or use of force short of war.[40]

6.4.2 International Political Transitions

Realists and liberals draw our attention to somewhat different past and ongoing transitions. On the realist side, Fig. 6.14 traces since 1960 the Hillebrand-Herman-Moyer power

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[39] See https://datagator.org/about.

[40] See Ghosn et al., 2004 for documentation related to version 3 of the MID dataset and the COW website at http://cow.dss.ucdavis.edu/data-sets/MIDs for version 4.2.

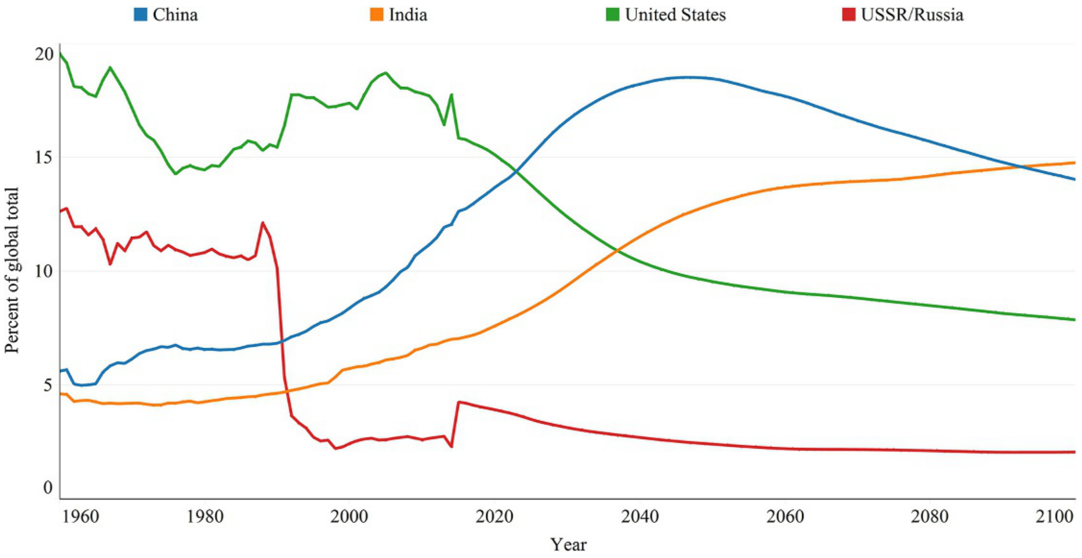

FIG. 6.14 **Power capabilities of major powers as portion of global total: History and IFs Base Case scenario to 2100.**

Note: Uses the Hillebrand-Herman-Moyer power index. The USSR is shown prior to 1990 and Russia thereafter. Source: IFs Version 7.36; historical data from multiple sources, including United Nations Population Division for population, World Development Indicators for GDP, and Stockholm International Peace Research Institute for military expenditures.

measure of IFs, showing the relative fall of Russia with the demise of the Soviet Union and the Cold War and the relative rise of China. The IFs Base Case scenario indicates the likely emergence of China as the relatively strongest global power before mid-century, followed later by a challenge from India. And interestingly, it shows that Chinese power relative to the United States has already surpassed the level of the USSR during the Cold War.

How different are portrayals in the IFs Base Case using different power measures? For the United States in 2015, the range of values across the three measures (not shown) was from 16% to 23%, with the Herman-Hillebrand-Moyer measure producing the lowest, the Global Power Index value the highest, and the Herman-Hillebrand measure a point near the center of the range. The measures change in parallel for the United States across this century in the IFs Base Case scenario, with a small degree of convergence. For China in 2015, the range across the three measures was only 2%, with the Herman-Hillebrand measure at the top. Across time the range for China expands to 5%, and the GPI provides the highest forecast. In summary, the portraits painted by the measures vary, but not dramatically.

Illustrating a more liberal perspective on global transition, Fig. 6.15 shows the growing rate of membership in intergovernmental organizations over time, reflecting also the growth in the number of those IGOs. Growth is the pattern across countries at all income levels. (The figure does not show a forecast because the early formulation in IFs for IGO memberships is largely extrapolative and remains under development.) Data in IFs show a similar historical upward movement of interstate connections via embassies and treaties.

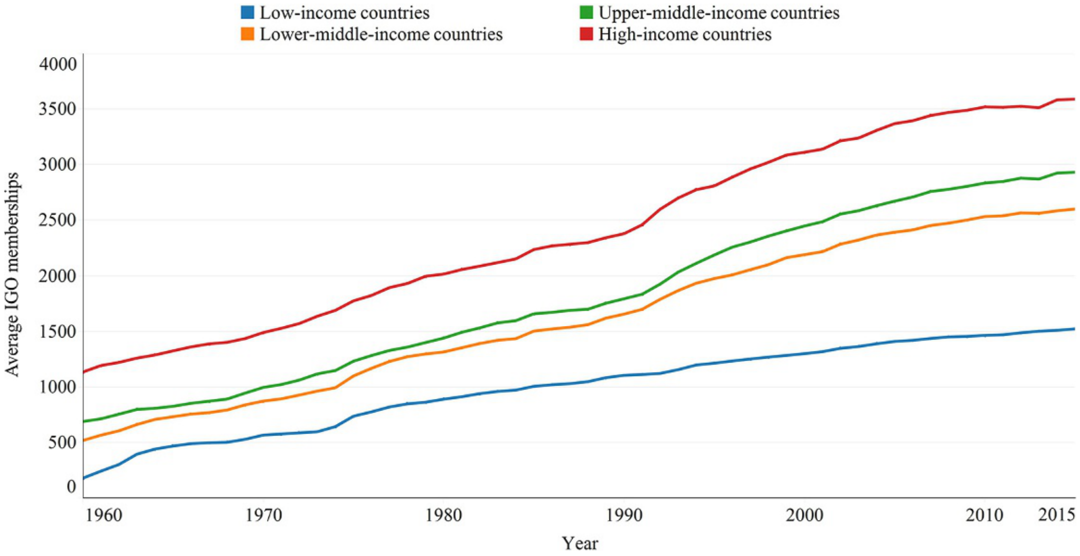

FIG. 6.15 **Number of intergovernmental organization (IGO) memberships by country economy classification from 1960–2015.**
Note: Uses World Bank classifications based on gross national income per capita. Numbers are simple averages of country values within each grouping. Source: IFs Version 7.36, using data from annual editions of the Union of International Associations' Yearbook of International Organizations.

6.4.3 Modeling International Politics

The focus of this volume is computerized forward-looking models. Although never developing a computer forecasting system himself, Harold Guetzkow (see Guetzkow, 1995) laid the foundations for much of the subsequent work on such models of international politics through his work on computer assisted gaming with the Inter-Nation Simulation (INS) and the larger Simulated International Processes research program (Guetzkow and Valadez, 1981). Building on INS, Bremer (1977) created perhaps the first computerized model of national decision-making as a bridge to those representing international politics.

The earliest international politics forecasting model of which I am aware was Simulating Political, Economic, and Strategic Interactions Among Major Powers (SIMPEST) developed by Luterbacher and Allan (1982); see also Siegmann (1987). Focusing especially on the United States, the Soviet Union, and China, SIMPEST represented the relationship of the economy, internal polity, and government domestically (including military spending both on conventional and nuclear forces) with action-reaction dynamics internationally.

While military spending and other elements of hard and soft power are key concepts in global politics, the variables of central interest are the potential for, and possible outcomes of, conflict. After two massive world wars and many other more locally devastating ones in the last century, forecasting must take seriously the potential for international conflict in the current century. Historical experience and power transition theory both suggest that system-wide conflict has high probability as a state rises in power near to, or more than, that of a former system leader in relative decline (Tammen et al., 2000). As China rises relative to the United States, there is a substantial debate in the mostly more-qualitative strategic foresight literature between those who see potential conflict (Allison, 2017; Layne, 2006, 2012; Mearsheimer, 2010; Schweller and Pu, 2011) and those who argue that this time may be different and that a new liberal global order may remain strong or even be strengthened (Chan, 2008; Ikenberry, 2008).

Even with quite strong conceptual and theoretical foundations, longer-term quantitative modeling of interstate conflict, or at least its probability, are all but nonexistent. One important step in that direction was the international political model within GLOBUS (Smith, 1987). Building on the COPDAB database, it initialized behavior and separately represented hostility sent and received within directed dyads, developing alternative scenarios for the US/USSR dyad. The core model structure was again an action-reaction dynamic (with roots back to Richardson, 1960), with reactivity related to the relative power of the states in the dyad as measured by accumulated military spending over time, trade relationships, and the broader systemic climate of relationships. Although its representation of dyadic relationships is not directional, the IFs approach has some similarities.

While not built to generate forecasts of interstate conflict, the statistically estimated multinomial logit model of Bennett and Stam (2003) integrated theoretical perspectives in a manner that has informed the development of IFs, as discussed later. Further, their associated, computerized Expected Utility Generation and Data Management Program (EUGene) software built upon that model and linked it to the expected utility framework of Bueno de Mesquita and Lalman (1992) for analysis and theory testing, if not forecasting.

6.4.4 International Politics in IFs

IFs models power in three alternative combinations of demographic, economic, military, technological, and diplomatic variables as described earlier. It then generates scenarios of the probability of conflict as a result of absolute and relative power levels, but also in response to other variables, including contiguity and great power status or lack thereof, democratization levels, extent of trade, and alliance relationships. This set of driving variables cuts across traditional realist and liberal perspectives.

Dichotomous (yes or no) country-year forecasts of international conflict would appropriately be subject to serious challenge. Gartzke (1999) clearly laid out the reality that empirical analysis can quite accurately identify cases (in IFs these are country-dyad years) of nonwar between states using variables such as a combination of inadequate power and too great a distance or lack of motivation. For cases other than those of nonwar, an outbreak depends on country interaction and negotiation dynamics (basically game-like) that make it probabilistic. Following the pattern of our treatment of internal conflict and the logic of Bennett and Stam (2003), IFs structurally identifies conditions that all but eliminate war probability (like those also identified by Gartzke). For the possible war cases, it uses a combined structural (largely algorithmic) and statistical approach that still does not produce binary conflict/no-conflict forecasts of war, but rather probability or threat of interstate violence. That allows the model to show, for example, increasing probability around the years of the nearly certain forthcoming power transition between the United States and China.

6.4.4.1 *Threat of Overt Conflict: General Challenges and Formulation*

Because of the importance of interstate violence, an IFs project sponsored by the Strategic Assessments Group of the US Central Intelligence Agency devoted effort to specifying the drivers of threat of conflict and then developing a formulation to create scenarios based on those drivers.[41] The resultant implementation of threat in IFs draws heavily on the MID database involving "the threat, display, or use of military force short of war" (Jones et al., 1996, p. 163). Some of the parameters for relationships in the IFs threat calculation were derived from a prepublication manuscript of Bennett and Stam (2003). Paul Senese estimated parameters for the democracy relationships from MID data, and Doug Lemke helped put together a set of estimated and literature-based parameters that helps determine most of the Base Case interstate conflict values in IFs.[42] The parameter determination was guided by desire to create a set of what economists sometimes call "stylized facts," indicating the contribution of various factors to higher or lower probabilities of conflict in a dyad. The need to address three challenges (discussed below) shaped the structure of the IFs system.

The first challenge: Using historical data to initialize threat levels versus using predictive formulations. The argument for using data to initialize dyadic threat levels is obvious: data tell us about historical relationships between countries, often carrying information that is not available in a predictive formulation (e.g., the historical conflict between India and Pakistan). Yet, the argument for not relying too heavily on such dyadic data in forecasting is also obvious; the US–Russian relationship, for example, fundamentally changed after the collapse of communism and the breakup of the Soviet Union. Still, the historical pattern of earlier data in that dyad did to some degree reassert itself over time, especially after the annexation of Crimea. Changes in the German–French relationship after World War II more strongly suggest how the power of historical patterns can fade. Thus while the IFs formulation provides forecasts that are rooted in data, it allows the ties to historical data to decay over time.

The second challenge: The complicated contributions and interaction of constant terms, switches, and variables. The single best predictor of conflict among countries historically may well be their physical proximity, with contiguous or geographically touching countries being far more conflict prone. However, because contiguity is a constant, it is nearly useless in determining how the threat of overt conflict will change in the future. Somewhat similarly, territorial disputes are highly persistent over time, but can be switched on or off in the world

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[41] With the title Threats and Opportunities AnalysiS (TAOS), and guided by Evan Hillebrand, the project drew together a number of experts to review and discuss enhancements to the IFs system, especially its representation of interstate politics. The participants were Stuart Bremer, Mark Crescenzi, Doug Lemke, Edward Mansfield, and Paul Senese. The project ultimately facilitated Barry Hughes's incorporation into IFs of insights from these individuals, including from their published work (see, for example, Crescenzi and Enterline, 2001 and Mansfield, 1994).

[42] Although none of the participants in that effort bears ultimate responsibility for the treatment of threat in IFs, the model owes a substantial debt to the participants in that project. Mark Crescenzi provided empirical initial conditions from the MID database using a technique for representing "memory" of past events (more distant events are less memorable) that he and Andrew Enterline pioneered (Crescenzi and Enterline, 2001). A significant problem was that the MID database used for the estimations extended only to 1992, so initial conditions for dyads involving Cold War adversaries were no longer credible after the end of the Cold War. Therefore, the IFs project used expert judgment to reset some of those values. The MID 4 update provides data through 2010, facilitating a recalculation of initial conditions that still does not reach the current IFs base year of 2015.

(and in a model). In contrast, power levels and commitment to democracy fluctuate substantially over time. Both types of variables (constant or near constant and fluctuating or changing) must enter into the formulation.

The third challenge: The contribution of power-based and other drivers. For purposes of clarity of conceptualization, there is value in distinguishing between drivers of threat that have their roots primarily in state power and those, like democracy level, that do not. To a significant degree they constitute two separate clusters, generally differentiating realist and liberal perspectives.

Taking into account these three foundational challenges, the IFs formulation of *THREAT* includes both a data-based term (*ThreatData*) and a prediction-based term (*ThreatPred*). The integrating equation shifts the forecast from exclusive use of the former to exclusive use of the latter over a time horizon that can be changed by the model user from a default value of 100 years, making it an important potential parameter for model sensitivity analysis (***wpthrconv***). The formulation is thus similar to others in IFs that reflect the importance of country-specific initial conditions in early years, but then gradually converge formulations to the more general ones based on distal and proximate drivers.

The initial value of the data term reflects the recent past of conflict in the dyad. The initial value of the predictive term reflects the relative power of the countries, their contiguity or lack thereof, and the existence of absence of territorial disputes. Neither term is static. Both change over time in response to change in the power and non-power sets of driving forces: one additive factor (*DeltaPowerTerms*) captures forecasted changes from the base year in power relationships, and a second additive factor (*DeltaNonPowerTerms*) captures changes in non-power relationships (such as democracy levels). Thus as these driving forces move the dyad away from initial conditions of the system, they also contribute to convergence in the values of the data-based and prediction-based terms.

$$THREAT_{act,tar} = ConvergeOverTime(ThreatData_{r=act,r=tar}, ThreatPred_{r=act,r=tar}, \boldsymbol{wpthrconv})$$

where

$$ThreatData_{r=act,r=tar} = ThreatData_{r=act,r=tar,t=1} + DeltaPowerTerms + DeltaNonPowerTerms$$

$$ThreatPred_{r=act,r=tar} = ThreatPred_{r=act,r=tar,t=1} + DeltaPowerTerms + DeltaNonPowerTerms$$

This top-level formulation points to the key elements that drive the forecast of threat. They fall into three general categories: the initial conditions of the *ThreatData* and *ThreatPred* terms; the evolution of *DeltaPowerTerms*; and the evolution of *DeltaNonPowerTerms*. We have already noted the reliance on the MID database to initialize the *ThreatData* term. The next sections sketch the computational systems underlying the other three terms; for full details, see Hughes, 2014.

6.4.4.2 Threat of Conflict: Initial Prediction Term

Predicted initial conflict threat level (*ThreatPred* at $t = 1$) comes from a formulation that relies on some of the strongest empirical predictors of interstate conflict. The first three are constant or switch factors: great power status of the dyad members (*GPowerTerm*);[43] contiguity

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[43] Hegre (2008) argued with an empirical basis from 1885 to 2001 that a gravity model representation of size and distance is superior to the use of a great power dummy in explaining conflict.

(*ContiguityTerm*); and existence of territorial dispute (*TerDisputeTerm*). All three terms substantially increase the threat of conflict. In addition, three terms decrease conflict: alliance (*AllyI*); minimum dyad democracy (*DemocTermMin*); and democratic distance (*DemocTermDist*). Each term merits some comment.

Great power status is often (for instance, in the Correlates of War project) determined subjectively, but modeling requires an objective definition of it. IFs designates any state below a lower threshold (***wpgreatthesh***—default value of 2% of systemic power) as a non-great power, and any state above an upper level (***wpgreatlev***—default value of 5%) as a great power, conferring partial status in between for selected computations, like that of systemic power concentration. The internal IFs variable *GPowerTermI* carries the resulting calculation of increased threat of conflict from great power status in the dyad, where ***wpgreat1*** determines the contribution of full great-power status and ***wpgreat2*** determines the contribution of partial great-power status.

Paul Diehl, former Director of the COW project, generously provided contiguity data for IFs (***contiguity***), and the parameter ***wpcontiguity*** translates the impact of contiguity into increased threat of conflict (*ContiguityTerm*). The work of Paul Huth (1996) was tapped for territorial disputes (*TerDispute*). The parameter ***wpterdisp*** translates the existence of a dispute into increased threat of conflict (*TerDisputeTerm*).

If any of these three factors (great power status, contiguity, and/or territorial dispute) is positive, the dyad members are "politically relevant" to each other, thereby increasing their sensitivity to other factors. In politically relevant dyads, IFs adds three factors to the predictive calculation of initial threat levels: a power transition term, an alliance term, and a two-term democracy representation. Again, each factor needs elaboration.

The initial power transition term (*PowerTranTermI*) begins with a computation of the ratio of power within the dyad. If that ratio exceeds a threshold level (***wppowtran1***), then the increased threat of conflict in the power transition term is set equal to the difference between the power ratio and the threshold power transition level, multiplied by an impact parameter (***wppowtran2***).

The second added factor is the alliance term (*AllyI*), which is simply the exogenously specified existence (1) or absence (0) of an alliance times a parameter (***wpally***) that translates alliance into conflict reduction. Turning to the third term, Senese (1997) found that the impact of democracy on the threat of conflict depends on both the lesser level of democracy in the states of the dyad and the difference between their levels. In IFs, the lesser or minimum level is multiplied by a parameter (***wpdemmin***) to determine the minimum democracy term (*DemocTermMin*), and the distance in democracy is multiplied by a second parameter (***wpdemdist***) to determine the contribution of the distance term to changed threat of conflict (*DemocTermDist*).

6.4.4.3 *Threat of Conflict: Dynamic Power Term*

The delta (change in) power terms variable (*DeltaPowerTerms*) is a sum of four other terms: delta great power term (*DeltaGPowerTerm*), delta power transition term (*DeltaPowerTranTerm*), delta territorial dispute term (*DeltaTerDisputeTerm*), and delta power concentration term (*DeltaConcenTerm*). The delta term for each is the calculation in a future year minus the initial value of the term. The only one of these terms not already discussed as part of the calculation of initial predicted threat is the delta power concentration term (*DeltaConcenTerm*).

Power concentration is a concept focusing on the degree to which the power structure of the great powers (not all powers in the system) is heavily concentrated or not. The interval data measure poses an alternative to the often less-systematic ordinal category estimation of whether a system is multipolar, bipolar, or unipolar (Singer et al., 1972). IFs calculates four versions of power concentration depending on the treatment of the European Union as an entity or as separate countries and depending on the power measure and the threshold definition of great powers (***wpgreatlev***)**.** The formulation normally uses the Hillebrand-Herman power measure (*POWER*) as summarized here:

$$PCONGREAT = \sqrt{\frac{SumSharesSQ - \frac{1}{SumGreat}}{1 - \frac{1}{SumGreat}}}$$

where

$$SumSharesSQ = \sum^{GPowers} \left(\frac{POWER_r}{\sum^{GPowers} POWER_r} \right)^2$$

$$SumGreat = Number\,of\,Great\,Powers$$

Mansfield (1994) investigated the relationship between the power concentration of great powers and propensity for war in the system and found a nonlinear pattern, with war most likely at highest and lowest system-concentration levels. Bennett and Stam (2003) investigated the relationship for militarized interstate disputes rather than wars and found parameters about half the magnitude that Mansfield reported for wars. IFs uses a Mansfield-type nonlinear formulation, with reduced parameters more appropriate to disputes rather than wars (remember that the IFs approach is a fundamentally stylized one, bringing together insights from much research rather than relying on a single statistically estimated function).

6.4.4.4 *Threat of Conflict: Dynamic Non-Power Term*

Again, the threat calculation builds on an initial constant term plus a delta power term and a delta non-power term. The non-power term (*DeltaNonPowerTerm*) is a sum of five other terms: delta minimum democracy term (*DeltaDemocTermMin*), delta democracy distance term (*DeltaDemocTermDist*), delta alliance term (*DeltaAllyTerm*), delta trade term (*DeltaTradeTerm*), and delta GDP growth term (*DeltaGDPGrowthTerm*). The delta term for each is the calculation in a future year minus the initial value of the term. Two of the five are used in forecast years but not in the initial year calculation: the delta trade term (*DeltaTradeTerm*) and the delta GDP growth term (*DeltaGDPGrowthTerm*).

The preponderance of empirical analysis appears to support the proposition that trade relationships reduce conflict, contributing with joint democracy to enhanced peace among states in the manner that Kant posited long ago.[44] Most empirical studies focus on trade specific to the dyad, generally using dyadic trade over GDP as a measure of trade dependence,

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[44] Immanuel Kant. 1795. "Perpetual Peace: A Philosophical Sketch." Available at https://slought.org/media/files/perpetual_peace.pdf.

and often focusing on the less dependent of the two trading partners (Oneal and Russett, 1997). Bennett and Stam (2003) support the general tendency of these conclusions. IFs does not represent dyadic trade in its default configuration (an option turns on bilateral trade), but Mansfield (1994) found that systemic trade over GDP is also inversely related to war, at least for the great powers. IFs includes such an inverse relationship with change in world trade as a percent of world GDP (*WTRADE*), controlling it by a parameter (***wptrade***).

Bennett and Stam (2003) also investigated the impact of global economic cycles and found that conflict propensity of all kinds roughly doubles during upswings relative to downswings. IFs introduces a factor that compares global economic growth (*WGDPR*) with the long-term pattern (*LongTermGDPR*), computed as a moving average. IFs translates the swings of growth into impact on threat with a parameter (***wpsysgr***), once again looking to Bennett and Stam for guidance on the magnitude of it.

6.4.4.5 Other Important Variables: Military Spending and Globalization

Building on the foundations of power and threat of conflict, IFs has forward linkages of potential importance. The first is to military spending, which is represented by an action-reaction dynamic related to the level of threat in each dyad. The second is to the outbreak of war and the consequences of it. As indicated earlier, we do not believe that we can forecast the timing of war, but on a wild-card scenario basis (and hardly ever used in analyses with IFs), the level of threat can trigger a stochastic process that generates a binary condition of war or lack thereof in every country dyad-year. Further, the model computes a very crude estimate of loss of life and destruction of capital stock in war years.

The combination of forecasting of international trade and international politics, along with other international variables (notably foreign direct investment, foreign assistance, and migration) in IFs, provides a foundation for looking at the extent to which countries are globalized and the pattern of possible globalization futures (Hughes, 2008). As discussed earlier, Diplometrics data projects at the Pardee Center are laying further groundwork for representation of additional dimensions of globalization.

6.4.4.6 Limitations

With respect to data, a high-priority need is to complete the updating of initial conditions for dyadic threat levels in IFs using the recently acquired update of MID data. Unfortunately, the new data still do not correspond to the model's base year because the MID project releases data with considerable lag.

Concerning conceptualization and formulations, considerable uncertainty and debate remain around both the meaning and measurement of power and threat of conflict. Together, our calculation of multiple measures of power and the ability of the user to change weightings in the basic power measure help address those uncertainties. Further, the very large-scale data development efforts of the IFs Diplometrics project are helping create foundations for further enhancing treatment of soft power/liberal paradigm elements.

Unfortunately, forecasting formulations remain uncertain and complicated for both domestic and international conflict. This is in significant part an unresolvable consequence of the two variables being highly volatile while the drivers of our formulations will continue to be much more slowly changing variables that reflect the gas on the rag rather than the sparks that might ignite it. Hence there is value in our representation of both types of conflict as probabilities rather than as discrete occurrences.

And finally, our formulation for threat of conflict does not yet represent the possibility that nonstate actors have (or will) become much more important either for better (conflict dampening, as a liberal school argues) or worse (as terrorism suggests is also possible).

6.4.5 Comparative Scenarios

Kugler and Tammen (2004, p. 50) forecast that China will overtake the United States in power within the next 30–50 years, before China is a fully developed country, making the overtaking similar to that of Germany by the USSR prior to World War II. They argued without quantification that the overtaking will increase the risk of conflict, which can in turn be lower if China is satisfied on issues such as the status of Taiwan. Overall, the argument is consistent with the notion of long cycles of rising powers and associated conflict in international politics (Modelski, 1987; Pop, 2017).

In spite of much speculation in qualitative analysis about the consequence of this pending power transition, I am aware of no quantitative forecasts of the long-term level of threat among global dyads other than those with IFs.[45] Fig. 6.16 shows the one from the IFs Base Case scenario for China and the United States, heavily influenced by the coming power transition (see again Fig. 6.14), but also taking into account the possibility of the movement by

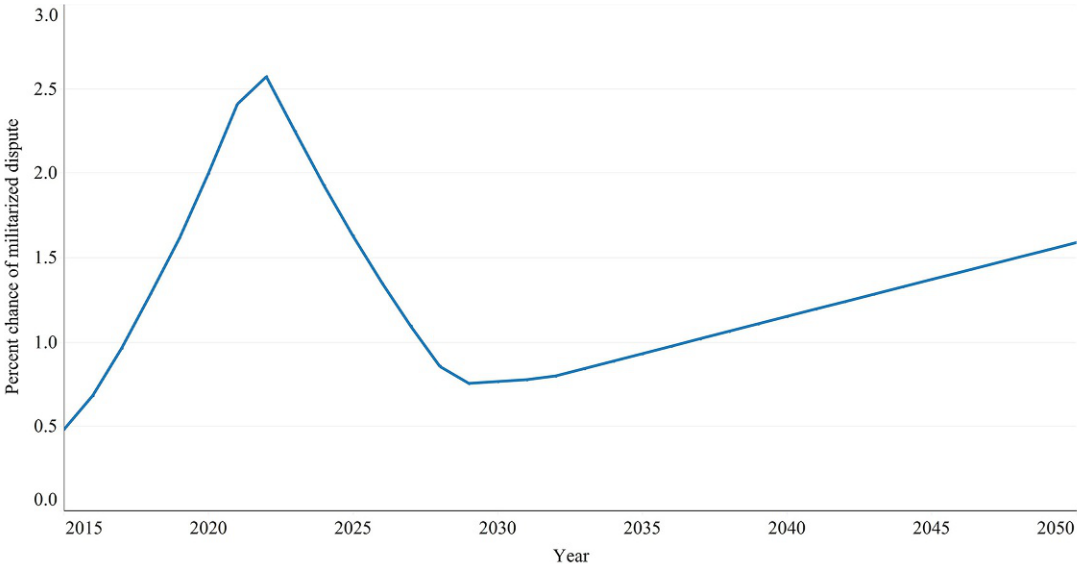

FIG. 6.16 **Annual threat of a militarized dispute between China and the United States: IFs Base Case scenario to 2050.**

Source: IFs Version 7.36, initialized with data from the Militarized Interstate Dispute database compiled by the Correlates of War Project.

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[45] In private correspondence with Håvard Hegre in October 2017, he was also unaware of others.

China through an anocratic period after completion of the power transition (Section 6.4.4.2 identified anocracy as increasing threat of domestic conflict, which can also spill over into international conflict). Earlier discussion indicated the great difficulty of structuring such forecasts, and it suggested the quite low level of confidence we should have in them. Again, however, the potential for regional or systemic warfare is too important a variable to omit from thinking about long-term global change.

6.5 CONCLUSION

Chapter 5 showed us the dramatic changes that have occurred in human development in recent decades and the longer term. It explained the basis within IFs for exploring possible future progress in human development—and the IFs Base Case does anticipate very substantial continued progress.

This chapter has traced no-less-dramatic historical and prospective change in social development. To a very considerable degree, this too has been a story of progress. Yet, there has been more volatile and sometimes cyclical behavior in the social sphere than in human development, including potential alternation in global economic leadership, cycles in domestic conflict, and shifting power balances globally. We turn now to the sustainability of development, where many point not only to critical and highly destructive long-term patterns of change, but also to the prospects of a perhaps significantly more challenging rather than better future.

References

Aghion, P., Durlauf, S.N. (Eds.), 2005. Handbook of Economic Growth, vols. 1A and 1B. Elsevier North-Holland, Amsterdam, the Netherlands.

Aghion, P., Howitt, P., 1992. A model of growth through creative destruction. Econometrica 60 (2), 323–351. https://dx.doi.org/10.3386/w3223.

Aguiar, A., Narayanan, B., McDougall, R., 2016. An overview of the GTAP 9 data base. J. Glob. Econ. Anal. 1 (1), 181–208. https://dx.doi.org/10.21642/JGEA.010103AF.

Allansson, M., Melander, E., Themnér, L., 2017. Organized violence, 1989–2016. J. Peace Res. 54 (4), 574–587. https://dx.doi.org/10.1177/0022343317718773.

Allen, R.D.B., 1968. Macro-Economic Theory. Macmillan, New York, NY.

Allison, G., 2017. Destined for War: Can America and China Escape Thucydides's Trap? Houghton Mifflin Harcourt, Boston, MA.

Andrews D., Sánchez A.C. and Johansson A., 2011. Towards a Better Understanding of the Informal Economy. OECD Economics Department Working Papers No. 873. OECD Publishing, Paris. https://doi.org/10.1787/5kgb1mf88x28-en.

Armington, P.S., 1969. A theory of demand for products distinguished by place of production. IMF Staff. Pap. 16 (1), 159–178. https://dx.doi.org/10.2307/3866403.

Asal, V., Pate, A., 2005. The decline of ethnic political discrimination, 1950–2003. In: Marshall, M.G., Gurr, T.R. (Eds.), Peace and Conflict 2005: A Global Survey of Armed Conflict, Self-Determination, and Democracy. University of Maryland Center for International Development and Conflict Management, College Park, MD, pp. 28–38.

Ayres, R.U., Warr, B., 2009. The Economic Growth Engine: How Energy and Work Drive Material Prosperity. Edward Elgar, Cheltenham, UK.

Azar, E.E., 1980. The conflict and peace data bank (COPDAB) project. J. Confl. Resolut. 24 (1), 143–152. https://dx.doi.org/10.1177/002200278002400106.

Backer, D.A., Bhavnani, R., Huth, P.K. (Eds.), 2017. Peace and Conflict 2017. Routledge, New York, NY.

Baldacci E., Clements B., Gupta S. and Cui Q., 2004. Social Spending, Human Capital, and Growth in Developing Countries: Implications for Achieving the MDGs. IMF Working Paper WP/04/217. International Monetary Fund, Washington, DC.

Baldwin, R., 2016. The Great Convergence: Information Technology and the New Globalization. Belknap Press, Cambridge, MA.

Barrios S., Pycroft J. and Saveyn B., 2013. The Marginal Cost of Public Funds in the EU: The Case of Labour versus Green Taxes. European Commission Taxation Papers Working Paper No. 35-2013. Publications Office of the European Union, Luxembourg. https://ec.europa.eu/taxation_customs/sites/taxation/files/resources/documents/taxation/gen_info/economic_analysis/tax_papers/taxation_paper_35_en.pdf.

Barro, R.J., 1996. Democracy and growth. J. Econ. Growth 1 (1), 1–27. https://dx.doi.org/10.1007/BF00163340.

Barro, R.J., 1999. Determinants of Economic Growth: A Cross-Country Empirical Study, second ed. MIT Press, Cambridge, MA.

Barro, R.J., Sala-i-Martin, X.X., 2004. Economic Growth. MIT Press, Cambridge, MA.

Benhabib, J., Spiegel, M.M., 1994. The role of human capital in economic development: evidence from aggregate cross-country data. J. Monet. Econ. 34 (2), 143–173. https://dx.doi.org/10.1016/0304-3932(94)90047-7.

Benhabib, J., Spiegel, M.M., 2005. Human capital and technology diffusion. In: Aghion, P., Durlauf, S.N. (Eds.), Handbook of Economic Growth, vol. 1A. Elsevier North-Holland, Amsterdam, The Netherlands, pp. 935–966.

Bennett, D.S., Stam, A.C., 2003. The Behavioral Origins of War: Cumulation and Limits to Knowledge in Understanding International Conflict. University of Michigan Press, Ann Arbor, MI.

Benos, N., Zotou, S., 2014. Education and economic growth: a meta-regression analysis. World Dev. 64 (December), 669–689. https://dx.doi.org/10.1016/j.worlddev.2014.06.034.

Berndt, E.R., Wood, D.O., 1975. Technology, prices, and the derived demand for energy. Rev. Econ. Stat. 57 (3), 259–268. Stable URL: http://www.jstor.org/stable/1923910.

Bohl, D., Hughes, B.B., Irfan, M., Margolese-Malin, E., Solórzano, J., 2017. The Informal Economy in the IFs Model. Report for Peru's Centro Nacional de Planeamiento Estratégico (CEPLAN). Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/Bohl_2015_Ceplan.pdf.

Bosworth, B.B., Collins, S.M., 2003. The Empirics of Growth: An Update. Economics of Developing Countries Paper. Brookings Institution, Washington, DC. https://www.brookings.edu/wp-content/uploads/2016/06/20030307-1.pdf.

Bowlsby, D., Chenoweth, E., Hendrix, C.S., Moyer, J.D., 2019 (forthcoming). Forecasting failures: temporal variation in drivers of political instability. Br. J. Political Sci. (in press).

Bremer, S.A., 1977. Simulated Worlds: A Computer Model of National Decision-Making. Princeton University Press, Princeton, NJ.

Bueno de Mesquita, B., 2002. Predicting Politics. Ohio State University Press, Columbus, OH.

Bueno de Mesquita, B., Lalman, D., 1992. War and Reason: Domestic and International Imperatives. Yale University Press, New Haven, CT.

Burke, M.B., Miguel, E., Satyanath, S., Dykema, J.A., Lobell, D.B., 2009. Warming increases the risk of civil war in Africa. Proc. Natl. Acad. Sci. U. S. A. 106 (49), 20670–20674. https://dx.doi.org/10.1073/pnas.0907998106.

Burt A., Hughes B.B. and Milante G., 2014. Eradicating Poverty in Fragile States: Prospects of Reaching the 'High-Hanging' Fruit by 2030. WB Policy Research Working Paper No. 7002. World Bank, Washington, DC. http://documents.worldbank.org/curated/en/2014/08/20040315/eradicating-poverty-fragile-states-prospects-reaching-high-hanging-fruit-2030.

Busby, J.W., Smith, T.G., White, K.L., Strange, S.M., 2013. Climate change and insecurity: mapping vulnerability in Africa. Int. Secur. 37 (4), 132–172. https://dx.doi.org/10.1162/ISEC_a_00116.

Calderón, C., Servén, L., 2010. Infrastructure and economic development in sub-saharan Africa. J. Afr. Econ. 19 (Suppl 1), i13–i87. https://dx.doi.org/10.1093/jae/ejp022.

Capros, P., van Regemorter, D., Paroussos, L., Karkatsoulis, P., 2013. Eradicating Poverty in Fragile States: Prospects of Reaching the 'High-Hanging' Fruit by 2030. WB Policy Research Working Paper No. 7002. Publications Office of the European Union, Luxembourg ftp://ftp.jrc.es/pub/EURdoc/JRC83177.pdf.

Carment, D., Prest, S., Samy, Y., 2010. Security, Development and the Fragile State: Bridging the Gap Between Theory and Policy. Routledge, Hoboken, NJ.

Chan, S., 2008. China, the U.S., and the Power-Transition Theory: A Critique. Routledge, New York, NY.

Chandy L., Ledlie N. and Penciakova V., 2013. The Final Countdown: Prospects for Ending Extreme Poverty by 2030. Policy Paper 2013-04. The Brookings Institution, Washington, DC. https://www.brookings.edu/wp-content/uploads/2016/06/The_Final_Countdown.pdf.

Chang, S.S.L., 1961. Synthesis of Optimum Control Systems. McGraw Hill, New York, NY.

Château J., Dellink R. and Lanzi E., 2014. An Overview of the OECD ENV-Linkages Model: Version 3. OECD Environment Working Paper No. 65. Organisation for Economic Co-operation and Development, Paris, France. https://doi.org/10.1787/5jz2qck2b2vd-en.

Chen, D.H.C., Dahlman, C.J., 2004. Knowledge and Development: A Cross-Section Approach. WB Policy Research Working Paper 3366. World Bank, Washington, DC. http://documents.worldbank.org/curated/en/681521468778205694/pdf/wps3366knowledge.pdf.

Chenery, H.B., 1979. Structural Change and Development Policy. Johns Hopkins University Press, Baltimore, MD.

Chenery, H.B., Syrquin, M., 1975. Patterns of Development, 1950–1970. Oxford University Press, London, UK.

Cincotta, R., 2018. The age-structural theory of state behavior. In: Thompson, W.R. (Ed.), Oxford Encyclopedia of Empirical International Relations Theory. Oxford University Press, New York, NY, pp. 44–64.

Cincotta, R.P., Doces, J., 2011. The age-structural maturity thesis: the impact of the youth bulge on the advent and stability of liberal democracy. In: Goldstone, J.A., Kaufmann, E., Toft, M.D. (Eds.), Political Demography: How Population Changes Are Reshaping Security and National Politics. Palgrave-MacMillan, Basingstoke, UK; New York, NY, pp. 98–116.

Cingranelli, D.L., Richards, D.L., 2010. The Cingranelli-Richards (CIRI) Human Rights Dataset Version 2010.08.15. Retrieved from, http://www.humanrightsdata.com/.

Cline, W.R., 2007. Global Warming and Agriculture: Impact Estimates by Country. Center for Global Development and Peterson Institute for International Economics, Washington, DC.

Collier, P., Hoeffler, A., 2004. Greed and grievance in civil war. Oxf. Econ. Pap. 56 (4), 563–595. https://dx.doi.org/10.1093/oep/gpf064.

CPB Netherlands Bureau for Economic Policy Analysis, 1999. WorldScan: The Core Version. CPB Special Publication 20. CPB Netherlands Bureau for Economic Policy Analysis, The Hague, The Netherlands. https://www.cpb.nl/sites/default/files/publicaties/download/worldscan-core-version.pdf.

Crescenzi, M.J.C., Enterline, A.J., 2001. Time remembered: a dynamic model of interstate interaction. Int. Stud. Q. 45 (3), 409–431. https://dx.doi.org/10.1111/0020-8833.00207.

Cuaresma, J.C., 2017. Income projections for climate change research: a framework based on human capital dynamics. Glob. Environ. Chang. 42 (January), 226–236. https://dx.doi.org/10.1016/j.gloenvcha.2015.02.012.

Cuaresma, J.C., Fengler, W., Kharas, H., Bekhtiar, K., Brottager, M., Hofer, M., 2018. Will the Sustainable Development Goals be fulfilled? Assessing present and future global poverty. Palgrave Communications 4: Article number 29 (unpaginated, open source). https://dx.doi.org/10.1057/s41599-018-0083-7.

Cusack, T., 1987. Government budget processes. In: Bremer, S.A. (Ed.), The GLOBUS Model: Computer Simulation of World-Wide Political and Economic Developments. Westview Press, Boulder, CO, pp. 325–458.

Dahl, R.A., 1957. The concept of power. Behav. Sci. 2 (3), 201–215. https://dx.doi.org/10.1002/bs.3830020303.

de la Maisonneuve, C., Oliveira Martins, J., 2015. The future of health and long-term care spending. OECD J. Econ. Stud. 2014 (1), 61–96. https://dx.doi.org/10.1787/eco_studies-v2014-1-en.

de Vries, G.J., Erumban, A.A., Timmer, M.P., Voskoboynikov, I.B., Harry, X.W., 2012. Deconstructing the BRICS: structural transformation and aggregate productivity growth. J. Comp. Econ. 40 (2), 211–227. https://dx.doi.org/10.2139/ssrn.1998072. DOI: 10.1787/eco_studies-2014-5jz0v44s66nw.

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the shared socioeconomic pathways. Glob. Environ. Chang. 42 (January), 200–214. https://dx.doi.org/10.1016/j.gloenvcha.2015.06.004.

Eberwein, W.-D., 1987. Domestic political processes. In: Bremer, S. (Ed.), The GLOBUS Model: Computer Simulation of World-Wide Political and Economic Developments. Westview Press, Boulder, CO, pp. 159–282.

Edward, P., Sumner A., 2013. The Geography of Inequality: Where and by How Much Has Income Distribution Changed since 1990? Working Paper 341. Center for Global Development, Washington, DC.

Erumban, A.A., de Vries K., 2016. Global Growth Projections for the Conference Board Global Economic Outlook 2017. Economics Program Working Paper Series EPWP #16-07. The Conference Board, New York, NY. https://www.conference-board.org/pdf_free/workingpapers/EPWP1607.pdf.

Esty, D.C., Goldstone, J.A., Gurr, T.R., Harff, B., Levy, M., Dabelko, G.D., et al., 1999. State failure task force report: phase II findings. Environ. Chang. Secur. Proj. Rep. 5 (Summer), 49–72. https://www.wilsoncenter./org/sites/default/files/Phase2.pdf.

Fabricant, S., 1954. Economic Progress and Economic Change. 34th Annual Report of the National Bureau of Economic Research. National Bureau of Economic Research, New York, NY.

Fouré, J., Fontagné, L., 2016. Long-Term Socio-Economic Scenarios for Representative Concentration Pathways Defining Alternative CO_2 Emission Trajectories. CEPII Research Report 2016-01. Centre d'Ėtudes Prospectives et d'Informations Internationales, Paris, France. http://www.cepii.fr/PDF_PUB/rr/rr2016_01.pdf.

Fund for Peace (FFP), 2012. The Failed States Index 2012. Fund for Peace, Washington, DC. http://library.fundforpeace.org/fsi12.

Gartzke, E., 1999. War is in the error term. Int. Organ. 53 (3), 567–587. https://dx.doi.org/10.1162/002081899550995.

Gehringer, A., Martinez-Zarzoso, I., Danzinger, F.N.-L., 2016. What are the drivers of total factor productivity in the European union? Econ. Innov. New Technol. 25 (4), 406–434. https://dx.doi.org/10.1080/10438599.2015.1067007.

Ghosn, F., Palmer, G., Bremer, S.A., 2004. The MID3 data set, 1993-2001: procedures, coding rules, and description. Conflict Manag. Peace Sci. 21 (2), 133–154. https://dx.doi.org/10.1080/07388940490463861.d.

Gleditsch, K.S., Ward, M.D., 1999. A revised list of independent states since the Congress of Vienna. Int. Interact. 25 (4), 393–413. https://dx.doi.org/10.1080/03050629908434958.

Gleditsch, N.P., Wallensteen, P., Eriksson, M., Sollenberg, M., Strand, H., 2002. Armed conflict 1946–2001: a new dataset. J. Peace Res. 39 (5), 615–637. https://dx.doi.org/10.1177/0022343302039005007.

Global Burden of Disease (GBD) Health Financing Collaborator Network, 2017. Future and potential spending on health 2015–2040: development assistance for health, and government, prepaid, private, and out-of-pocket health spending in 184 countries. Lancet 389 (10083), 2005–2030. https://dx.doi.org/10.1016/S0140-6736(17)30873-5.

Goldstone, J.A., Bates, R.H., Epstein, D.L., Gurr, T.R., Lustik, M.B., Marshall, M.G., et al., 2010. A global model for forecasting political instability. Am. J. Polit. Sci. 54 (1), 190–208. https://dx.doi.org/10.1111/j.1540-5907.2009.00426.x.

Grossman, G.M., Helpman, E., 1994. Endogenous innovation in the theory of growth. J. Econ. Perspect. 8 (1), 23–44. http://www.jstor.org.du.idm.oclc.org/stable/2138149.

Guetzkow, H., 1995. Recollections about the inter-nation simulation (INS) and some derivatives in global modeling. Simul. Games 26 (4), 453–470. https://dx.doi.org/10.1177/1046878195264007.

Guetzkow, H., Valadez, J.J. (Eds.), 1981. Simulated International Processes: Theories and Research in Global Modeling. Sage, Beverly Hills, CA.

Gurr, T.R., Lichbach, M.I., 1986. Forecasting internal conflict: a competitive evaluation of empirical theories. Comp. Pol. Stud. 19 (1), 3–38. https://dx.doi.org/10.1177/0010414086019001001.

Halperin, M., Siegle, J.T., Weinstein, M.M., 2004. The Democracy Advantage: How Democracies Promote Prosperity and Peace. Routledge, New York, NY.

Hanushek, E.A., Woessmann, L., 2010. Education and economic growth. In: Peterson, P., Baker, E., McGaw, B. (Eds.), International Encyclopedia of Education. In: Vol. 2. Elsevier, Oxford, UK, pp. 245–252.

Hanushek, E.A., Woessmann, L., 2015. The Knowledge Capital of Nations: Education and the Economics of Growth. MIT Press, Cambridge, MA.

Hanushek, E.A., Jamison, D.T., Jamison, E.A., Woessmann, L., 2008. Education and economic growth. Educ. Next. 8 (2) unpaginated. http://educationnext.org/education-and-economic-growth/.

Hawksworth, J., Chan, D., 2015. The World in 2050: Will the Shift in Global Economic Power Continue? PricewaterhouseCoopers, Economics and Policy Team, London, UK. https://www.pwc.com/gx/en/issues/the-economy/assets/world-in-2050-february-2015.pdf.

Hegre, H., 2008. Gravitating toward war: preponderance may pacify, but power kills. J. Confl. Resolut. 52 (4), 566–589. https://dx.doi.org/10.1177/0022002708316738.

Hegre, H., Karlsen, J., Nygård, H.M., Strand, H., Urdal, H., 2013. Predicting armed conflict, 2010–2050. Int. Stud. Q. 57 (2), 250–270. https://dx.doi.org/10.1111/isqu.12007.

Hegre, H., Buhaug, H., Calvin, K.C., Nordkvelle, J., Waldhoff, S.T., Gilmore, E., 2016a. Forecasting civil conflict along the shared socioeconomic pathways. Environ. Res. Lett.. 11(5). https://dx.doi.org/10.1088/1748-9326/11/5/054002.

Hegre, H., Nygård, H.M., Dahlum, S., Karlsen, J., 2016b. The Next 50 Years of Democracy: Forecasting Regime Types, 2013–2062. Unpublished manuscript.

Hegre, H., Metternich, N.W., Nygård, H.M., Wucherpfennig, J.W., 2017. Introduction: forecasting in peace research. J. Peace Res. 54 (2), 113–124. https://dx.doi.org/10.1177/0022343317691330.

Hewitt, J.J., Wilkenfeld, J., Gurr, T.R., 2012. Peace and Conflict 2012. Paradigm, Boulder, CO.

Horowitz, K.J., Planting, M.A., 2006. Concepts and Methods of the Input-Output Accounts. Handbook. Bureau of Economic Analysis, U.S. Department of Commerce, Washington, DC.

Hughes, B.B., 1997. Continuity and Change in World Politics: Competing Perspectives, third ed. Prentice Hall, Upper Saddle River, NJ.

Hughes, B.B., 2005. Forecasting Productivity and Growth with International Futures (IFs), Part 1: The Productivity Formulation. Working Paper 2005.05.24.a. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/2005.05.24.a_IFsDocumentation_Productivity_Part_1_v2.pdf.

Hughes, B.B., 2007. Forecasting Global Economic Growth with Endogenous Multifactor Productivity: The International Futures (IFs) Approach. Working Paper 2007.12.31. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/forecasting-global-economic-growth-endogenous-multifactor-productivity-international-futures-ifs.

Hughes, B.B., 2008. Forecasting globalization: the use of International Futures (IFs). In: Modelski, G., Devezas, T., Thompson, W.R. (Eds.), Globalization as Evolutionary Process: Modeling Global Change. Routledge, New York, NY, pp. 355–379.

Hughes, B.B., 2014. IFs Interstate Politics Model Documentation. Working Paper 2014.02.17. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/ifs-interstate-politics-model-documentation.

Hughes, B.B., 2015. IFs Economic Model Documentation. Working Paper 2015.07.20. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/Economics%20Documentation%20v43%20clean.pdf.

Hughes, B.B., Hillebrand, E.E., 2006. Exploring and Shaping International Futures. Paradigm, Boulder, CO.

Hughes, B.B., Hossain, A., 2004. Long-Term Socio-Economic Modeling (with Universal, Globally-Integrated Social Accounting Matrices in a General Equilibrium Model Structure). Working Paper 2004.05.07. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/2004.05.07_IFsDocumentation_Socioeconomic_with_SAM_v47.pdf.

Hughes, B.B., Irfan, M.T., 2013. The Data Preprocessor of International Futures (IFs). Working Paper 2013.07.12. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://www.pardee.du.edu/sites/default/files/2013.07.12_IFsDocumentation_Data_PreProcessor_v37.pdf.

Hughes, B.B., Irfan, M.T., Khan, H., Kumar, K.B., Rothman, D.S., Solórzano, J.R., 2009. Reducing Global Poverty. Patterns of Potential Human Progress Series, , vol. 1. Paradigm Publishers and Oxford University Press, Boulder, CO; New Delhi, India.

Hughes, B.B., Moyer, J.D., Sisk, T.D., 2011. Vulnerability to interstate conflict: evaluating quantitative measures. Peaceworks report No. 72. United States Institute of Peace, Washington, DC. http://www.usip.org/sites/default/files/Vulnerability_to_Intrastate_Conflict.pdf.

Hughes, B.B., Joshi, D.K., Moyer, J.D., Sisk, T.D., Solórzano, J.R., 2014. Strengthening Governance Globally. Patterns of Potential Human Progress Series, , vol. 5. Paradigm Publishers and Oxford University Press, Boulder, CO; New Delhi, India.

Huntington, S., 1991. The Third Wave: Democratization in the Late Twentieth Century. University of Oklahoma, Norman, OK.

Huth, P., 1996. Standing Your Ground: Territorial Disputes and International Conflict. University of Michigan Press, Ann Arbor, MI.

Ikenberry, G.J., 2008. The rise of China and the future of the west. *Foreign Affairs*. (January/February issue). http://www.foreignaffairs.com/articles/63042/g-john-ikenberry/the-rise-of-china-and-the-future-of-the-west.

Inglehart, R., 1997. Modernization and Postmodernization. Princeton University Press, Princeton, NJ.

Inglehart, R., Welzel, C., 2005. Modernization, Cultural Change, and Democracy: The Human Development Sequence. Cambridge University Press, Cambridge, MA.

Jamison, D.T., Lau, L.J., Wang, J., 2005. Health's contribution to economic growth in an environment of partially endogenous technical progress. In: López-Casanovas, G., Rivera, B., Currais, L. (Eds.), Health and Economic Growth: Findings and Policy Implications. MIT Press, Cambridge, MA, pp. 67–92.

Jones, D.M., Bremer, S.A., Singer, J.D., 1996. Militarized interstate disputes, 1816-1992: rationale, coding rules, and empirical patterns. Conflict Manag. Peace Sci. 15 (2), 163–215. https://dx.doi.org/10.1177/073889429601500203.

Joshi, D.K., 2011. Multi-party democracies and rapid economic growth: a 21st century breakthrough? Taiwan J. Democr. 7 (1), 25–46.

Joshi, D.K., Hughes, B.B., Sisk, T.D., 2015. Improving governance for the post-2015 sustainable development goals: scenario forecasting the next 50 years. World Dev. 70 (June), 286–302. https://dx.doi.org/10.1016/j.worlddev.2015.01.013.

Kaufmann, D., Kraay, A., Mastruzzi, M., 2010. The Worldwide Governance Indicators: Methodology and Analytical Issues. WB Policy Research Working Paper No. 5430. World Bank, Washington, DC. http://documents.worldbank.org/curated/en/630421468336563314/pdf/WPS5430.pdf.

Keohane, R.O., Nye Jr., J.S., 1987. Power and interdependence revisited. Int. Organ. 41 (4), 725–753. Stable URL: http://www.jstor.org/stable/2706764.

Kriegler, E., Mouratiadou, I., Luderer, G., Bauer, N., Calvin, K., DeCian, E., et al., 2013. RoSE: Roadmaps towards Sustainable Energy Futures and Climate Protection: A Synthesis of Results from the RoSE Project. AMPERE Consortium. Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany. http://www.rose-project.org/Content/Public/RoSE_REPORT_310513_ES.pdf.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V.J., Petermann, N., Bosetti, V., et al., 2015. Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. Technol. Forecast. Soc. Chang. 90 (Part A), 24–44. https://dx.doi.org/10.1016/j.techfore.2013.09.021.

Kriegler, E., Mouratiadou, I., Luderer, G., Edmonds, J., Edenhofer, O., 2016. Introduction to the RoSE special issue on the impact of economic growth and fossil fuel availability on climate protection. Clim. Chang. 136 (1), 1–6. https://dx.doi.org/10.1007/s10584-016-1667-4.

Kugler, J., Tammen, R.L., 2004. Regional challenge: China's rise to power. In: Rolfe, J. (Ed.), The Asia-Pacific: A Region in Transition. Asia-Pacific Center for Security Studies, Honolulu, HI, pp. 33–53.

Kuznets, S., 1955. Economic growth and income inequality. Am. Econ. Rev. 45 (1), 1–28. https://www.jstor.org/stable/1811581.

Kuznets, S., 1959. On comparative study of economic structure and growth of nations. In: Goldsmith, R.W. (Ed.), The Comparative Study of Economic Growth and Structure. National Bureau of Economic Research, New York, NY, pp. 162–176.

Kypreos, S., Bahn, O., 2003. A MERGE model with endogenous technological progress. Environ. Model. Assess. 8 (3), 249–259. https://dx.doi.org/10.1023/A:1025551408939.

Layne, C., 2006. The unipolar illusion revisited: the coming end of the United States' unipolar moment. Int. Secur. 31 (2), 7–41. https://dx.doi.org/10.1162/isec.2006.31.2.7.

Layne, C., 2012. This time it's real: the end of unipolarity and the pax Americana. Int. Stud. Q. 56 (1), 203–213. https://dx.doi.org/10.1111/j.1468-2478.2011.00704.x.

Lee, R.D., Mason, A. (Eds.), 2011. Population Aging and the Generational Economy: A Global Perspective. Edward Elgar, Cheltenham, UK.

Leimbach, M., Kriegler, E., Roming, N., Schwanitz, J., 2017. Future growth patterns of world regions–a GDP scenario approach. Glob. Environ. Chang. 42 (January), 215–225. https://dx.doi.org/10.1016/j.gloenvcha.2015.02.005.

Lejour, A., Veenendaal, P., Verweij, G., van Leeuwen, N., 2006. WorldScan: A Model for International Economic Policy Analysis. CPB Document No. 111. CPB Netherlands Bureau for Economic Policy Analysis, The Hague, the Netherlands. http://www.cpb.nl/en/publication/worldscan-model-international-economic-policy-analysis.

Leontief, W., 1951. The Structure of the American Economy, 1919–1939, second ed. International Arts and Sciences Press, White Plains, NY.

Loayza, N.V., 2016. Informality in the Process of Development and Growth. WB Policy Research Working Paper No. 7858. World Bank, Washington, DC.

Lofgren, H., Díaz-Bonilla, C., 2010. MAMS: An economy-wide model for analysis of MDG country strategies—an application to Latin America and the Caribbean. In: Sanchez, M.V., Vos, R., Ganuza, E., Lofgren, H., Díaz-Bonilla, C. (Eds.), Public Policies for Human Development: Achieving the Millennium Development Goals in Latin America. Palgrave Macmillan, New York, NY, pp. 71–126.

Lührmann, A., Lindberg, S.I., Mechkova, V., Olin, M., Casagrande, F.P., Petrarca, C.S., et al., 2017. Democracy at Dusk? V-Dem Annual Report 2017. V-Dem Institute, University of Gothenburg, Gothenburg, Sweden. https://www.v-dem.net/en/news-publications/annual-report/.

Luterbacher, U., Allan, P., 1982. Modeling politico-economic interactions within and between nations. Int. Polit. Sci. Rev. 3 (4), 404–433. https://dx.doi.org/10.1177/019251218200300404.

Maddison, A., 2001. The World Economy: A Millennial Perspective. Organisation for Economic Co-operation and Development, Paris, France.

Maddison, A., 2003. The World Economy: Historical Statistics. Organisation for Economic Co-operation and Development, Paris, France.

Maddison, A., 2007. Contours of the World Economy, 1–2030 AD. Oxford University Press, New York, NY.

Mankiw, N.G., Romer, D., Weil, D.N., 1992. A contribution to the empirics of economic growth. Q. J. Econ. 107 (2), 407–437. https://dx.doi.org/10.2307/2118477.

Mansfield, E.D., 1994. Power, Trade, and War. Princeton University Press, Princeton, NJ.

Marshall, M.G., 2016. Major Episodes of Political Violence (MEPV) and Conflict Regions, 1946-2015. Codebook. Center for Systemic Peace, Vienna, VA. Available at http://www.systemicpeace.org/inscr/MEPVcodebook2015.pdf.

Marshall, M.G., Cole, B.R., 2014. Global Report 2014: Conflict, Governance, and State Fragility. Center for Systemic Peace, Vienna, VA. http://www.systemicpeace.org/vlibrary/GlobalReport2014.pdf.

Marshall, M., Gurr, T.R., Harff, B., 2015. PITF–State Failure Problem Set: Internal Wars and Failures of Governance, 1955–2014. Dataset and Coding Guidelines. Societal Systems Research, Inc, Vienna, VA. Retrieved from, http://www.systemicpeace.org/inscr/PITFProbSetCodebook2014.pdf.

Marshall, M.G., Gurr, T.R., Jaggers, K., 2016. Polity IV Project: Political Regime Characteristics and Transitions 1800–2015. Dataset Users' Manual. Center for Systemic Peace, Vienna, VA. http://www.systemicpeace.org/inscr/p4manualv2015.pdf.

Mearsheimer, J.J., 2010. The gathering storm: China's challenge to U.S. power in Asia. Chin. J. Int. Polit. 3 (4), 381–396. https://dx.doi.org/10.1093/cjip/poq016.

Mesarovic, M.D., Pestel, E. (Eds.), 1974. Multilevel Computer Model of World Development System, vol. 1–6. Extracts from Symposium Proceedings, Laxenburg, Austria, April 29–May 3, 1974. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Milante, G., Hughes, B.B., Burt, A., 2016. Poverty eradication in fragile places: prospects for harvesting the highest hanging fruit by 2030. Stab. Int. J. Secur. Dev. 5 (1), 1–24. https://dx.doi.org/10.5334/sta.435.

Mishkin, E., Braun, L. (Eds.), 1961. Adaptive Control Systems. McGraw Hill, New York, NY.

Modelski, G., 1987. Long Cycles in World Politics. Palgrave Macmillan, London, UK.

Modigliani, F., 1986. Life cycle, individual thrift, and the wealth of nations. Am. Econ. Rev. 76 (3), 297–313. Stable URL: http://links.jstor.org/sici?sici=0002-8282%28198606%2976%3A3%3C297%3ALCITAT%3E2.0.CO%3B2-I.

Morgenthau, H.J., 1973. Politics Among Nations: The Struggle for Power and Peace. Alfred A. Knopf, New York, NY.

Moyer, J.D., Sweijs, T., Burrows, M.J., van Manen, H., 2017. Power and Influence in a Globalized World. Atlantic Council, Washington, DC.

Nelson, R.R., Phelps, E.S., 1966. Investment in humans, technological diffusion, and economic growth. Am. Econ. Rev. 56 (1/2), 69–75. Stable URL: http://links.jstor.org/sici?sici=0002-8282%28196603%2956%3A1%2F2%3C69%3AIIHTDA%3E2.0.CO%3B2-E.

Nye Jr., J.S., 2004. Soft Power: The Means to Success in World Politics, first ed. Public Affairs, New York, NY.

Oneal, J.R., Russett, B.M., 1997. The classical liberals were right: democracy, interdependence, and conflict, 1950–1985. Int. Stud. Q. 41 (2), 267–294. https://dx.doi.org/10.1111/1468-2478.00042.

Organisation for Economic Co-operation and Development (OECD), 2001. OECD Economic Outlook No. 69. Edition 2001/1. OECD Publishing, Paris, France. https://books.google.co.in/books?id=uCOkDWiIa7sC&pg=PR6&lpg=PR6&dq=oecd+economic+outlook+edition+2001/1&source=bl&ots=AZTfKbkCDX&sig=kTN0GbHYKbYQNTQUgoxQngDQ-IM&hl=en&sa=X&redir_esc=y#v=onepage&q=oecd%20economic%20outlook%20edition%202001%2F1&f=false.

Organisation for Economic Co-operation and Development (OECD), 2003. The Sources of Economic Growth in OECD Countries. OECD, Paris, France. https://dx.doi.org/10.1787/9789264199460-en.

Organisation for Economic Co-operation and Development (OECD), 2017a. Geographical Distribution of Financial Flows to Developing Countries: Disbursements, Commitments, Country Indicators. OECD Publishing, Paris, France. https://dx.doi.org/10.1787/fin_flows_dev-2017-en-fr.

Organisation for Economic Co-operation and Development (OECD), 2017b. Pensions at a Glance 2017: OECD and G20 Indicators. OECD Publishing, Paris, France. https://dx.doi.org/10.1787/pension_glance-2017-en.

Oviedo, A.M., Thomas, M.R., Karakurum-Özdemir, K., 2009. Economic Informality: Causes, Costs, and Policies—A Literature Survey. WB Working Paper No. 167. World Bank, Washington, DC.

Pelinescu, E., 2015. The impact of human capital on economic growth. Procedia Econ. Financ. 22 (December), 184–190. https://dx.doi.org/10.1016/S2212-5671(15)00258-0.

Piketty, T., 2014. Capital in the Twenty-First Century. Belknap Press, Cambridge, MA.

Pop, A., 2017. Long cycles and anticipation. In: Poli, R. (Ed.), Handbook of Anticipation: Theoretical and Applied Aspects of the Use of Future in Decision Making. Springer Nature. https://link.springer.com/referenceworkentry/10.1007/978-3-319-31737-3_85-1 Forthcoming printed version in 2020 through Springer International Publishing.

Prichard, W., Cobham, A., Goodall, A., 2014. The ICTD Government Revenue Dataset. ICTD Working Paper No. 19. International Centre for Tax and Development, Institute of Development Studies, Brighton, UK. http://www.ictd.ac/publication/2-working-papers/12-the-ictd-government-revenue-dataset.

Przeworski, A., Limongi, F., 1997. Modernization: theories and facts. World Polit. 49 (2), 155–183. https://dx.doi.org/10.1353/wp.1997.0004.

Przeworski, A., Alvarez, M.E., Antonio Cheibub, J., Limongi, F., 2000. Democracy and Development: Political Institutions and Well-Being in the World, 1950–1990. Cambridge University Press, New York, NY.

Puddington, A., Roylance, T., 2017. The freedom house survey for 2016: the dual threat of populists and autocrats. J. Democr. 28 (2), 105–119. https://dx.doi.org/10.1353/jod.2017.0019.

Rao, N.D., Sauer, P., Gidden, M., Riahi, K., 2018. Income inequality projections for the Shared Socioeconomic Pathways (SSPs). Accepted August 1 for publication in Futures; available from authors by request at. https://www.researchgate.net/publication/326790004_Income_inequality_projections_for_the_Shared_Socioeconomic_Pathways_SSPs.

Ravallion, M., 2013. How Long Will It Take to Lift One Billion People Out of Poverty? WB Policy Research Working Paper No. 6325. World Bank, Washington, DC.

Ray, J.L., 1990. Global Politics, fourth ed. Houghton Mifflin, Boston, MA.

Ray, J.L., Singer, J.D., 1973. Measuring the concentration of power in the international system. Sociol. Methods Res. 1 (4), 403–436. https://dx.doi.org/10.1177/004912417300100401.

Richardson, L.F., 1960. Arms and Insecurity: A Mathematical Study of the Causes and Origins of War. Quadrangle Books, Chicago, IL.

Romer, P.M., 1990. Endogenous technological change. J. Polit. Econ. 98 (5, Part 2), S71–S102. http://www.jstor.org.du.idm.oclc.org/stable/2937632.

Romer, P.M, 1994. The origins of endogenous growth. J. Econ. Perspect. 8 (1), 3–22. https://dx.doi.org/10.1257/jep.8.1.3.

Sachs, J., 2005. The End of Poverty: Economic Possibilities for Our Time. Penguin Press, New York, NY.

Sarkees, M.R., Wayman, F.W., 2010. Resort to War: 1816–2007. Congressional Quarterly Press, Washington, DC.

Sauer, P., Rao, N., Pachauri, S., 2016. Explaining Income Inequality Trends in Countries: An Integrated Approach. Paper prepared for the 34th International Association for Research in Income and Wealth (IARIW) General Conference, Dresden, Germany, August 21–27. http://www.iariw.org/dresden/sauer.pdf.

Schneider, F., Enste, D.H., 2000. Shadow economies: size, causes, and consequences. J. Econ. Lit. 38 (1), 77–114. https://dx.doi.org/10.1257/jel.38.177.

Schrodt, P.A., Davis, S.G., Weddle, J.L., 1994. Political science: KEDS–a program for the machine coding of event data. Soc. Sci. Comput. Rev. 12 (4), 561–587.

Schweller, R.L., Pu, X., 2011. After unipolarity: China's visions of international order in an era of U.S. decline. International Security 36 (1), 41–72.

Senese, P.D., 1997. Between dispute and war: the effect of joint democracy on interstate conflict escalation. J. Polit. 59 (1), 1–27.

Siegmann, H., 1987. World Modeling. Report. International Institute for Comparative Social Research (Wissenschaftszentrum), Berlin, Germany, originally 1985. Archived by UNESCO at. http://unesdoc.unesco.org/images/0008/000890/089016eo.pdf.

Singer, J.D., Bremer, S.A., Stuckey, J., 1972. Capability distribution, uncertainty, and major power war, 1820–1965. In: Russett, B.M. (Ed.), Peace, War and Numbers. Free Press, New York, NY, pp. 19–48.

Small, M., Singer, J.D., 1982. Resort to Arms: International and Civil Wars, 1816–1980. Sage, Beverly Hills, CA.

Smith, D.L., 1987. International political processes. In: Bremer, S.A. (Ed.), The GLOBUS Model: Computer Simulation of Worldwide Political and Economic Developments. Westview Press, Boulder, CO, pp. 569–711.

Solow, R.M., 1956. A contribution to the theory of economic growth. Q. J. Econ. 70 (1), 65–94. https://dx.doi.org/10.2307/1884513.

Solow, R.M., 1957. Technical change and the aggregate production function. Rev. Econ. Stat. 39 (3), 312–320. https://dx.doi.org/10.2307/1926047.

Syrquin, M., Chenery, H., 1989. Three decades of industrialization. World Bank Econ. Rev. 3 (2), 145–181. https://dx.doi.org/10.1093/wber/3.2.145.

Tammen, R.L., Kugler, J., Lemke, D., Stam III, A.C., Alsharabati, C., Abdollahian, M.A., et al., 2000. Power Transitions: Strategies for the 21st Century. Chatham House, New York, NY.

Taylor, L., 1979. Macro Models for Developing Countries. McGraw-Hill, New York, NY.

Thyne, C.L., 2006. ABC's, 123's, and the golden rule: the pacifying effect of education on civil war, 1980–1999. Int. Stud. Q. 50 (4), 733–754. https://dx.doi.org/10.1111/j.1468-2478.2006.00423.x.

Transparency International, 2016. Corruption Perceptions Index 2016: Technical Methodology Note. Transparency International Secretariat, Berlin, Germany. Document available by selecting "Technical Methodology Note" under Downloads header at. https://www.transparency.org/news/feature/corruption_perceptions_index_2016.

Urdal, H., 2006. A clash of generations? Youth bulges and political violence. Int. Stud. Q. 50 (3), 607–629. Stable URL: http://www.jstor.org/stable/4092795.

van der Mensbrugghe, D., 2010. The ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model, Version 7.1. World Bank, Washington, DC. http://siteresources.worldbank.org/INTPROSPECTS/Resources/334934-1314986341738/Env7_1Jan10b.pdf.

van der Mensbrugghe, D., 2011. LINKAGE Technical Reference Document, Version 7.1. World Bank, Washington, DC. http://siteresources.worldbank.org/INTPROSPECTS/Resources/334934-1314986341738/TechRef7.1_01Mar2011.pdf.

van der Mensbrugghe, Dominique. n.d. "Shared Socio-Economic Pathways and Global Income Distribution." Unpublished paper available at https://www.gtap.agecon.purdue.edu/resources/download/7554.pdf.

Vos, R., 1989. Accounting for the world economy. Rev. Income Wealth 35 (4), 389–408. https://dx.doi.org/10.1111/j.1475-4991.1989.tb00600.x.

Vos, R., de Jong, N., 1995. Trade and financial flows in a world accounting framework: a balanced WAM for 1990. Rev. Income Wealth 41 (2), 139–159. https://dx.doi.org/10.1111/j.1475-4991.1995.tb00105.x.

Vreeland, J.R., 2008. The effect of political regime on civil war: unpacking anocracy. J. Confl. Resolut. 52 (1), 401–425.

Wagner, A., 1892. Grundlegung der Politischen Ökonomie. C. F. Winter, Leipzig, Germany.

Waltz, K.N., 1979. Theory of International Politics. Random House, New York, NY.

Waltz, K.N., 2000. Structural realism after the cold war. Int. Secur. 25 (1), 5–41. https://dx.doi.org/10.1162/016228800560372.

Weber, M., 1978. Roth, G., Wittich, C. (Eds.), Economy and Society: An Outline of Interpretive Sociology. University of California Press, Berkeley, CA. Translation of Wirtschaft and Gesellschaft.

Welzel, C., 2013. Freedom Rising: Human Empowerment and the Quest for Emancipation. Cambridge University Press, New York, NY.

Wixted, B., Yamano, N., Webb, C., 2006. Input-Output Analysis in an Increasingly Globalised World: Applications of OECD's Harmonised International Tables. STI Working Paper 2006/7. Organisation for Economic Co-operation and Development, Paris. http://www.oecd.org/science/sci-tech/37349386.pdf.

Woltjer, G., Kuiper, M., 2014. The MAGNET Model: Module Description. Manual LEI 14-057. Wageningen University and Research (WUR), The Hague, the Netherlands. http://www.magnet-model.org/MagnetModuleDescription.pdf.

World Bank, 1997. World Development Report 1997: The State in a Changing World. Oxford University Press, New York, NY.

Further Reading

Chung-I Li, J., 2002. A 1998 Social Accounting Matrix (SAM) for Thailand. TMD Discussion Paper No. 95. Trade and Macroeconomics Division, International Food Policy Research Institute, Washington, DC.

CHAPTER

7

The Future of Sustainable Development

Enhancing the human condition requires development and spread of human capabilities and wellbeing as well as of supportive social systems. We have been managing those in fits and starts across millennia, and we continue to work on them. It requires also that our larger biophysical environment support us and that, in turn, we abuse it as little as possible.

Unfortunately, we have long, often, and significantly abused it, as illustrated by the extent of early deforestation and soil loss in countries around the Mediterranean Sea. In his own study of that devastation, McNeil (1992) looked back more than 2000 years to the writing of Plato in his dialogue *Critias*, where Plato said that after thousands of years of human impact

> …Athens is now like … a sick body with barely any flesh on it. In those early days the land was unspoilt; there was soil high upon the mountains… There was abundant timber on the mountains…Some of our mountains can now only support bees. (McNeil, 1992, p. 72)

Human activity interfaces with the environment in everything we do, and some areas of interface place especially great demands on it. The first is our need for constant sustenance. As of 2015 (using values in International Futures [IFs] from multiple sources, especially the Food and Agriculture Organization of the United Nations, or FAO), our food systems had become massive agricultural operations that used almost 6 billion hectares of land (about 40% of the earth's total land) for raising crops and grazing food animals. The second is our desire to harness energy beyond that of our own bodies. Globally in 2017, each person, on average, used commercial energy equivalent to about 1853 L of gasoline (70.4 gigajoules), mostly in the form of burning fossil fuels; those in high-income countries almost literally burned through about 5270 L (196.4 gigajoules). A third area that places great demand on the environment is our infrastructure system. For example, we have constructed nearly 40 million kilometers of road around the world, of which nearly two-thirds are paved; more than 70% of all persons in rural areas live within two kilometers of an all-weather road with many consequent environmental impacts, including disruption of animal movement.

International Futures
https://doi.org/10.1016/B978-0-12-804271-7.00007-5

This chapter undertakes two highly interrelated tasks. It looks first (Sections 7.1–7.3) at these human systems (agriculture, energy, and infrastructure) that bridge our activities most strongly to the environment, with one eye on the support they provide for human wellbeing and the other on the stress that they place on the environment. Second, in Sections 7.4–7.6, it turns more directly to the modeling of change in two biophysical systems that our activities heavily affect—climate and water. (Another heavily affected system, which IFs does not represent, is biodiversity.) What the chapter does not do is consider the impact of environmental change (especially that of climate) back to human systems. Chapter 8 addresses that topic.

7.1 AGRICULTURE AND FOOD

There are two important types of accounting systems for relationships among humans, agriculture, and the environment. The first represents the value of agriculture for humans. We can measure this in currency terms or in physical ones, such as metric tons of crops, meat, and fish produced, and in calories, proteins, and other nutrients delivered. The second accounting system is impact on the environment of these activities, especially with respect to land and water use.[1] I focus here on the former and return to impacts later in the chapter.

7.1.1 Concepts, Structures, and Data

Briefly stated, the accounting that needs to be maintained around agricultural supply and the meeting of human demand consists of gross production, loss of production (in the field in the processing, transport, and distribution chain, and by consumers), exchange, including trade, and final consumption, mostly by people directly as food but also by other food sources (e.g., the use of low food-chain wild fish to feed more highly valued ones in aquaculture, and of grain to feed animals) and in industry (e.g., grain for alcoholic beverages and fibers for textiles). All of these are annual flows, just as supply and demand are accounted for in economic forecasting. The key difference is that in agriculture modeling they are represented initially in physical terms, whereas in economic modeling the primary focus is on value (such as US dollars) with price changes often in index form. Stocks are important primarily in two ways: (1) as productive resources, including land, labor, capital, water, technology, animal herds, and fish stocks (both wild and cultivated) and (2) as inventories of food carried across years and the signals those give to demand–supply equilibration processes.

The data for agriculture modeling come overwhelmingly from the FAO. Its database, FAOSTAT, covers production, trade, food balances, prices, investment, and land use, with many series back to 1961. FAOSTAT is the source for agriculture data in this section unless otherwise noted.

Chapter 6 emphasized the uncertainty around supply-side variables in the long-term forecasting of economics, especially productivity of labor and capital (see Section 6.1.3). The same is true for agriculture (and energy, discussed later in this chapter). The longer-term demand

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[1] The list of variables of potential interest is, of course, longer and potentially includes soil loss, chemical deposition, and more.

side is relatively freer of uncertainty, tied as it is to population size, income levels, and physical needs and desires. Although the source of calories consumed is important, and the mix of vegetable, meat, and fish sources around the world varies considerably, most societies want their agricultural systems to supply somewhat more than 3000 kcal per person per day on average, not all of which will be directly consumed.[2]

There is an important exception to the weight given below to the supply side. In the shorter run, and especially for lower-income countries, the push to eliminate hunger requires special attention to the demand side. The primary uncertainty with respect to effective food demand is income, not physical desire. For instance, a Pardee Center project sponsored by the New Partnership for African Development to study the ability of Africa to eliminate hunger and food insecurity by 2025 found it critical to explore the degree to which Africans would have adequate effective (income-based) demand to secure food, even if their countries could produce adequate quantities (Hedden et al., 2016).

In the longer term, there is more controversy concerning whether levels of calorie demand can be met for the 10 billion probably fairly well-to-do people the world will have later in this century. Further, that uncertainty focuses on yield levels. Whereas for almost all of human history agricultural land expansion was the key to expanding food supplies, land under cultivation is no longer changing dramatically around the world; between 1961 and 1991 global cropland rose by only 15% and grazing area by 7.5%, and since that time both have seen little change. Instead, in recent decades, growth in production per unit of land—its yield—has become the path to expansion of supplies; globally yield rose by nearly 80% between 1961 and 1991 and increased a further 36% through 2013.

7.1.2 Agriculture and Food Transitions

There is no more important transition around food and agriculture than the growing availability of nutrients globally. Fig. 7.1 shows growth in calorie availability since 1961. The most striking aspect of the graphic is that in 1961 all country groupings other than today's high-income category had average calories per day of about 2000 or less (1800 or less for an individual is often considered survival threatening). Over a period of 54 years, calories per capita rose in each country-income category (albeit largely leveling out for high-income countries in recent years). The most significant growth has been in the upper-middle-income category, dominated demographically by China but experiencing large gains much more broadly (the values for that grouping in 1961 were at the starvation level because of the disastrous "Great Leap Forward" of China in 1958–1961). Lower-middle-income countries have made lesser but important progress, and low-income countries have done least well. The spread of gross calorie availability in recent years shows clearly the importance of income in driving the ability to acquire food. In 1961 all three developing country groupings had GDP per capita values less than $2000 (even using $2011 at purchasing power parity [PPP]). In 2015, the values were $13,100, $5597, and $1546, respectively.

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[2] Following common practice (see http://who.int/nutrition/topics/3_foodconsumption/en/), when we refer to calorie consumption it means calories available for consumption. Among other factors, waste reduces actual consumption; physical needs for best health are less than 3000 kcal daily.

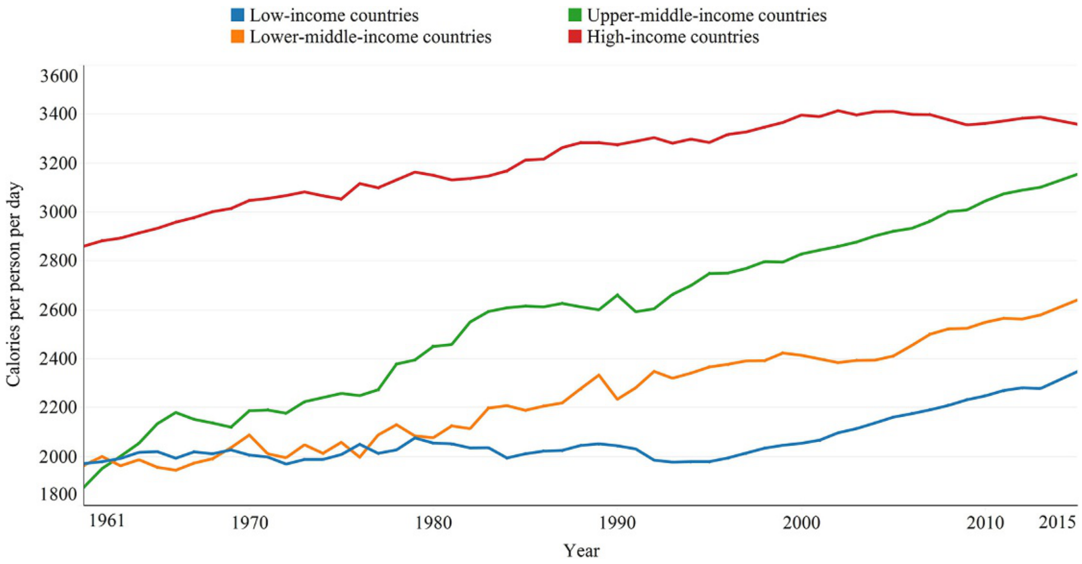

FIG. 7.1 **Available calories per day by country economy classification from 1961 to 2015.**
Note: Uses World Bank classifications based on gross national income per capita, and combines calories from crops, meat, and fish in population-weighted country-category averages; values in 2014–2015 are IFs estimates.
Source: IFs Version 7.36, using data from the Food and Agriculture Organization of the United Nations through 2013.

The global shortage of calories, and thus food production, to feed all current humans at the level of high-income countries is 15% (IFs-based calculations). Although income is the dominant variable in determining per capita food demand, it is obviously important that the world not only close that gap but further increase production across time to meet population-based demand growth. And even with trade, countries and regions will need to meet most demand increase internally. Unlike the situation with energy, where about 45% of global fossil fuel production was exported in 2015, a relatively small fraction of agricultural output is traded across countries. In 1961, global crop exports accounted for less than 7% of the 2.2 billion metric tons of crop production, and by 2013 that had climbed to only 13% of the nearly four times higher global production.

As noted earlier, agricultural use of land has expanded dramatically over time. Global cropland area grew from about 4206 km^2 in 1700 to 18,106 in the 1990s, and croplands, pasture, and rangelands now account for nearly 50% of the world's potentially vegetated land surface (Bondeau et al., 2007, p. 680). Therefore the potential for further growth in cropland area has become limited.

Fig. 7.2 shows the rapid growth in agricultural yields over time, but with income-category patterns quite different from those of calorie consumption. Already in the early 1960s, yield levels were higher in upper-middle-income countries than in high-income ones, and that is now true also in lower middle-income countries. Obviously, yield variation can reflect land and climate differences. It can also be responsive to differences in population density and the need for localized production. In IFs-based calculations for 2015, the population per hectare of cropland was about 5.6 and 6.0 in upper-middle-income and lower-middle-income countries

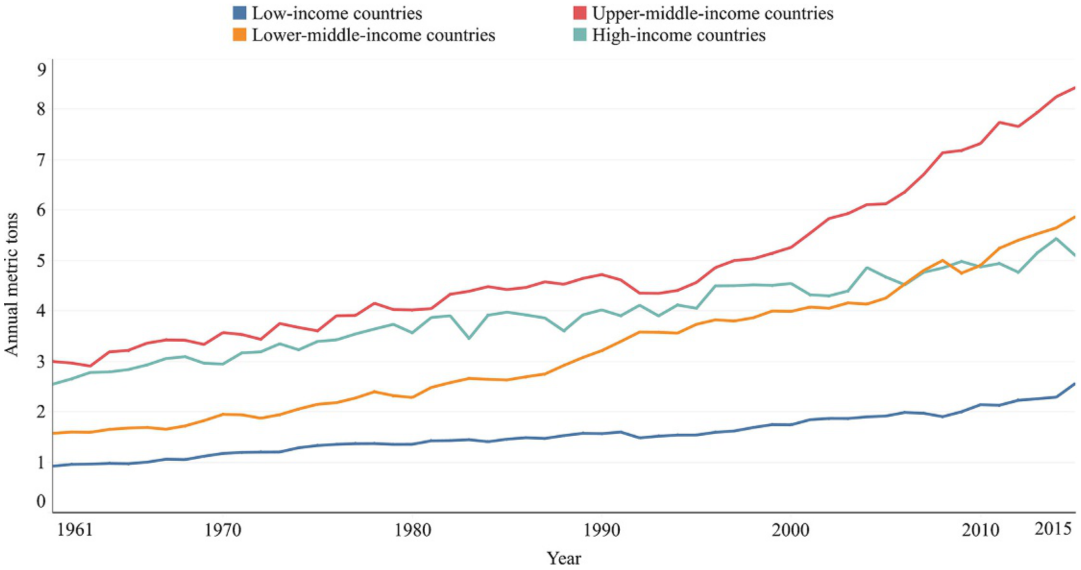

FIG. 7.2 **Crop yield (pre-loss) per hectare of cropland by country economy classification from 1961to 2015.** *Note: Uses World Bank classifications based on gross national income per capita; yield values for 2014–2015 are IFs estimates of cropland-weighted group averages.*
Source: IFs Version 7.36, using data from the Food and Agriculture Organization of the United Nations through 2013.

respectively, whereas it was about 4.1 in low-income countries and only about 2.5 in high-income countries. The central importance of yields to keeping food available focuses model attention to its forecasting.

7.1.3 Modeling Agriculture and Food

It is possible to make useful food and agriculture forecasts without formal models. In fact, the FAO has provided widely used estimates through 2050 with a projection methodology that relies heavily upon expert judgment (Alexandratos and Bruinsma, 2012, pp. 137–139). The methodology begins with Engel function-based (i.e., income-related) demand estimations that use exogenous population and GDP forecasts, followed by assumptions about trade and food sufficiency, to develop initial estimations of commodity production by country. Accounting consistency is maintained via several rounds of adjustments, based on the judgment of specialists on demand, nutrition, land, and yield.

Turning to formal models, the International Food Policy Research Institute is the home of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Robinson et al., 2015; Rosegrant and IMPACT Development Team, 2012). The IMPACT system has roots back to the early 1990s and has been widely used in analyses, including those of water demand and supply with its integrated water simulation models. Version 3 represents 62 agricultural commodities (crops and meat, not fish) and 159 countries; in interaction with 154 hydrological basins, there are 320 food production units. Equations use the

General Algebraic Modeling System (GAMS) and prices equilibrate global supply and demand for the commodities; the time horizon is 2050.

Yield in IMPACT responds over the longer run to an exogenous trend (with slowing increase), climate, and irrigation, and in the shorter term to both input and output prices (Robinson et al., 2015, p. 13). The model uses an activity-commodity approach to facilitate value-chain analysis. It differentiates land, and therefore yield, in irrigated and rain-fed systems. Alternative assumptions about the trend of yields are important in IMPACT scenario analysis. The project has drawn upon a separate model of 42 crops (the Decision Support System for Agrotechnology Transfer, or DSSAT) that helps represent the influence of climate.[3]

Trade puts net exports/imports into a pool in IMPACT and is not bilateral (Stehfest et al., 2013, p. 41). The larger model system links information from climate, crop simulation, and water models to a partial equilibrium multimarket economic model focused on the agriculture sector (Robinson et al., 2015, p. vii). Population and GDP, needed for the demand side, are exogenous. A website allows various projections to be accessed.[4]

The standard model of the Global Trade and Analysis Project (GTAP) is a computable general equilibrium (CGE) system, but the project's heavy focus on agricultural sectors of the economy supported a model extension called LEITAP[5] (now MAGNET, a general equilibrium model with many agricultural sectors, see Stehfest et al., 2014, p. 111). Analysis with IMAGE has compared agricultural system response to dietary changes in the projections of LEITAP/MAGNET and IMPACT (Stehfest et al., 2013, p. 38).

In addition to general agricultural models like IMPACT and MAGNET that give broad attention to supply and demand and linkages to other systems like economics, there are many models more focused on crop production and/or general vegetation conditions, often in combination with land use and with special attention to the impacts of climate change. For instance, the Environmental Policy Integrated Climate (EPIC) model projects growth of 80 crops.[6]

The Global Biosphere Management Model (GLOBIOM) of the International Institute for Applied Systems Analysis (IIASA) represents the competition for land use across agricultural, forestry, and bioenergy uses in 30 world regions with 18 crop types.[7] GLOBIOM is more elaborate on the supply than the demand side. On the supply side, the project has collected an extremely rich database of land with grid-based as well as country resolution differentiated by altitude, slope, and soil classes. General land classes in the model are cropland, grassland, managed forest, unmanaged forest, protected forest, short rotation plantations, and land

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[3] DSSAT is open source at https://dssat.net/about.

[4] See also http://impact-model.ifpri.org/#methodology, which links to a page for pulling up model results.

[5] The LEITAP model (Landbouw Economisch Institute Trade Analysis Project) was developed by Landbouw Economisch Instituut (LEI Agricultural Economics Institute) at Wageningen University. See http://www.magnet-model.org/about.aspx on MAGNET.

[6] See https://blackland.tamu.edu/models/epic/.

[7] See http://data.ene.iiasa.ac.at/message-globiom/land_use/index.html. Documentation of GLOBIOM at http://ec.europa.eu/clima/policies/strategies/analysis/models/docs/globiom_en.pdf suggests 50 regions (of which 27 are EU states, apparently often consolidated) and 20 crops. The combined MESSAGE-GLOBIOM system has 11 regions, see http://themasites.pbl.nl/models/advance/index.php/Spatial_dimension_-_MESSAGE-GLOBIOM.

under other natural vegetation. Cropland management systems differentiate irrigated, high-input rainfed, low-input rainfed, and subsistence categories. Yield growth is partly exogenous and partly endogenous. Much analysis with the system focuses on the carbon source and sink implications of alternative land uses.

Originally the product of a consortium and now based at the Potsdam Institute for Climate Impact Research (PIK), LPJmL (Lund-Potsdam-Jena managed Land) "simulates vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems."[8] It represents agricultural yield under "optimal management intensities" (Stehfest et al., 2014, p. 189), and the IAM IMAGE suite uses it to calculate yields with regional management intensities from the MAGNET model. It is gridded, and outputs can be specified to be daily, monthly, or annually. In addition to being incorporated into IMAGE, LPJmL has been linked to the MAgPIE and REMIND models (see again Section 3.2.1).

Also based at PIK, the Model of Agricultural Production and its Impact on the Environment) (MAgPIE) is a 10-region recursive dynamic optimization global land-use model connected to the gridded LPJmL.[9] It provides economic context to LPJmL, including agricultural demand, investment, and production costs, and in turn takes information, such as yields and land and water constraints, from LPJmL. (MAgPIE identifies sub-Saharan Africa, the Middle East, and South Asia as the regions with greatest potential for increased yield.)

GLOBIO is another related model built for analysis of environmental impacts; in this case, the impact of human population on biodiversity.[10] Based, like IMAGE, at the PBL Netherlands Environmental Assessment Agency, GLOBIO is given inputs from IMAGE to evaluate consequences for biodiversity at regional and global scales. There is also an aquatic version of GLOBIO (Stehfest et al., 2014, p. 247) focused on inland water systems, including wetlands.

Many broader integrated assessment models have been connected via hard or soft linkages with IMPACT, GLOBIOM, MAGNET, MAgPIE, or other models for agriculture, land, and biodiversity analysis. For instance, the IMAGE suite includes a variety of hard and soft linkages to many such models, including being soft linked with MAGNET, which takes forecasts on land and yield impact of climate from IMAGE and, in turn, feeds information on endogenous yield change and production to IMAGE. IMAGE itself represents gridded land cover and use and irrigation, and it further uses the LPJmL model for dynamic calculations of global vegetation, agriculture, and hydrology (Stehfest et al., 2014, p. 187).

The website of the Agricultural Model Intercomparison and Improvement Project (AgMIP)[11] is a portal to information on many agriculture and land-use models beyond those noted so far. Most are specialized for countries or regions of the world and/or to particular

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[8] From description of LPJmL model at https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml. The model is available on GitHub at https://github.com/PIK-LPJmL/LPJmL.

[9] See description of MAgPIE at https://www.pik-potsdam.de/research/projects/activities/land-use-modelling/magpie/magpie-2013-model-of-agricultural-production-and-its-impact-on-the-environment. See also Dietrich et al., 2014.

[10] For technical documentation of GLOBIO, see http://www.pbl.nl/en/publications/globio-35-technical-model-description.

[11] See http://www.agmip.org/.

aspects of agriculture, including specific crops. von Lampe et al. (2014) reported from an AgMIP study of agricultural futures across 10 models and across scenarios with different assumptions, including those about climate change (no change or RCP8.5, see subsequent climate change discussion in Section 7.5.3) and socioeconomic conditions (SSP2 or SSP3; see Section 3.3.2.1 on the SSPs). Among the findings were that CGE models (such as MAGNET, ENVISAGE, and AIM), tended to produce lower producer prices than partial equilibrium agriculture models (including GLOBIOM, IMPACT, and MagPIE) in the common reference scenario and to indicate less rise in prices with alternative assumptions, including climate change; this is related to greater representation of substitution in production and demand systems in the CGE models. The study also stressed the importance of income elasticities of demand (known to be less than 1.0 for staples) and of uncertainties around land use, yield growth, and prices. Even in the common reference scenario, average annual change in real producer prices between 2005 and 2050 varied across models from −0.4% to +0.7% (prices actually declined 4% between the 1960s and 2000s).

In short, there is a wide range of approaches to modeling the future of global agriculture. Most represent demand for food and even the process of equilibrating demand and supply. While demand is the dominant driver of agricultural systems, greater uncertainties exist around production patterns and cost structures on the supply side, and essentially all models find it important to dig deeply into patterns of supply. Uncertainty about supply, including the impact of climate change, tends also to be the focus of scenario analysis. For instance, Rosenzweig et al. (2014) compared crop yields in global gridded crop models across four alternative RCPs (representative concentration pathways, see Section 7.5.3) so as to vary climate change futures. They found significant variation by latitude and crop, but a relatively narrow approximate band of 10% decrease or increase in yields by end of century relative to base projections.

7.1.4 Agriculture and Food in IFs[12]

The IFs agriculture model is a country-specific partial equilibrium model of physical land and food systems that is hard-linked to, and elaborates, the currency-based agricultural sector in the IFs general equilibrium economic model (see Section 6.1.4). Partial equilibrium physical systems have significant advantages in providing commodity-specific information within a sector. On the other hand, general equilibrium systems have advantages in accounting across sectors for production-side inputs such as capital and labor (thereby imposing trade-offs across sectors). They also have advantages in representing forward linkages from sectors to the broader economy and to variables, such as income, that then, in turn, have broader implications (such as in the computation of food demand). Strongly linking the two types of models thus has benefits for the forecasting of both.

The IFs agriculture model endogenously incorporates—albeit in simpler, non-gridded form than more specialized agriculture and land-use models—a representation of land (differentiated by cropland, grazing land, forest, developed land, and other), agricultural production (crops, meat, and fish), various types of agricultural demand (food, feed, and

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[12] In 2015, Dale Rothman undertook a substantial update and revision of the IFs agriculture and food model, including the addition of protein representation and the tying of the IFs database directly to FAO statistics at a more disaggregated level than allowed by earlier use in IFs of aggregate crop production data categories.

industrial use), trade (globally), equilibrating supply–demand balance, and resultant nutrition (calories and proteins). The physical representations are transformed to currency values for input into (as with investment demand) or override of (as with food production, demand, and trade) the agricultural sector in the economic model.

The hard links of the agriculture model to other models in IFs involve many causal connections. For instance, deforestation is linked to greenhouse emissions, and changes in temperature and precipitation from global warming feed back to crop yields. The water model responds to demand for irrigation water and feeds back water availability to irrigation extent, again with implications for yield. Forward linkages from agriculture include undernutrition levels, important to the health model. In short, IFs includes most of the main features desired for analysis of key issues around agriculture, with a special focus on food provision but, at least at this time, omission of agriculture's impact on biodiversity.

In its data preprocessor, IFs aggregates the FAO's specific food-type data so as to represent only three categories of agricultural production and consumption: crops, meat, and fish. This process obviously combines a huge number of species, creating some complications. One complication is that the apparent consumption (production plus imports minus exports) of crops in different countries will not in reality yield anywhere near the same calories per ton. Consider a country like Uganda in which agricultural production might include much coffee. Calorie content of coffee is very different from that for rice or corn (as is dollar value in trade). We use country-specific adjustment or shift factors to take such country differences into account.

As suggested earlier, given population and income forecasts from the respective models in IFs, food demand is relatively less complicated to project than agricultural supply. We therefore give most attention in the sections that follow to supply variables and their drivers. For full model documentation, see http://pardee.du.edu/wiki/Main_Page.

7.1.4.1 Yield and Production

Crop production is a product of the cropland under cultivation and the yield per hectare of land. IFs determines yield in a Cobb–Douglas-type production function, the inputs to which are agricultural capital, labor, and technical change. Technical change responds to price signals, but the model also directly uses the imbalance between computations of food stocks and desired food stocks to enhance equilibrating responsiveness.[13] Overall, basic annual yield growth is bound by the maximum of the initial model year's yield growth for each country and an exogenous parameter of maximum growth.

This basic yield function is further subject to a saturation factor computed internally to the model, such that investments in increasing yield are subject to diminishing rather than constant returns to scale. Moreover, changes in atmospheric carbon dioxide (CO_2) affect agricultural yields, for the most part negatively through changes in temperature and precipitation, but also positively through CO_2 fertilization. Finally, the user can rely on a multiplier parameter to increase or decrease yield patterns directly, while other parameters control the saturation effect and scale the combined effects of CO_2 on crop yield.[14]

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[13] The structure could have been built only on prices, but the recursive structure makes feedback faster with stocks.

[14] Most contemporary agriculture models introduce slowing of yield growth due to climate change impacts (for example, see Figure 6.2.2 in Stehfest et al., 2014, p. 191) and/or slowing demand growth, but not necessarily via saturation of yields with approach to photosynthetic limits or other ultimate production constraints.

Basic yield function. To be more specific, crop production (*AGP*) is the product of yield (*YL*) and land devoted to crops (*LD*).[15]

$$AGP_{r,f=1} = YL_r * LD_{r,l=1}$$

IFs computes yield in stages using a Cobb–Douglas form with saturation. The first stage provides a basic yield responsive to the long-term developmental factors, namely capital, labor, and technology. It distinguishes between the yields of irrigated and non-irrigated land. The second stage uses this basic yield as an input and modifies it based on prices and food stocks so as to represent changes in shorter-term and more proximate factors. Finally, in a third stage, yields are adjusted in response to changing climate conditions.

The basic yield (*BYl*) relates yield to agricultural capital (*KAG*), agricultural labor (*LABS*), technological advance (*AgTec*), a scaling parameter (*CoDoug*) computed in the first model year, an exponent (*CDALF*), and a saturation coefficient (*SatK*).

$$BYl_r = CoDoug_{r,t=1} * AgTec_{r,t} * KAG_r^{CDALF_{r,s=1}} * LABS_{r,s=1}^{\left(1-CDALF_{r,s=1}\right)} * SatK_r$$

CDALF is the standard Cobb–Douglas alpha reflecting the relative elasticities of yield to capital and labor. It is computed each year in a function rooted in data on factor shares from GTAP and driven by GDP per capita at PPP.

Agriculture technology term in the yield function. *AgTec* is a factor-neutral technological progress coefficient similar to a multifactor productivity coefficient. It is initially set to one and changes each year based upon a technological growth rate (*YlGroTech*). The recursive model structure requires a one-year lag in impact of technology in the equation above, while the equation below computes it in the current year.

$$AgTec_r = AgTec_{r,t} * (1 + YlGroTech_r)$$

The algorithmic structure for computing the annual values of *YlGroTech* involves three elements:

- An underlying long-term rate of growth in agricultural productivity, computed in the initial model year as the difference between country-specific long-term yield growth and the portion of that growth attributable to increase of capital and labor. This basic growth rate is subject to saturating potential and will decline over time; the default in IFs currently assumes decrease by half over 100 years.
- The underlying growth in agricultural productivity logically should also be subject to variation in technological advance more generally. IFs introduces this by modifying the growth rate additively with the change in the larger economic model's productivity rate relative to the base year. Thus it reflects changes in the contributions of human, social, physical, and knowledge capital to general technological advance of the society, as discussed in Section 6.1.4.1 with respect to the IFs economic model.
- Finally, even though the basic technological term is subject to some saturation, the product of the preceding elements is multiplied by a saturation coefficient (*SatK*) that explicitly introduces assumptions about potential maximum yield (see discussion in the following section).

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[15] See Box 5.1 as needed for explanation of equation notation.

Saturation coefficient in agriculture. The saturation coefficient is a multiplier of the Cobb–Douglas function and the technological change element. It is the ratio of the gap between maximum possible yield (*YLLim*) and a moving average of yields (*SYl*) to the gap between that maximum possible yield and the initial yield, raised to an exogenous yield exponent (***ylexp***). With positive parameters, the form produces decreasing marginal returns.

$$SatK_{r+1} = \left(\frac{YlLim_r - SYl_r}{YlLim_r - YL_{r,t=1}}\right)^{\boldsymbol{ylexp}}$$

where

SYl_r is a moving average of *BYl*, the historical component of which is weighted by one minus the user-controlled global parameter ***ylhw***

The maximum possible yield (*YlLim*) is estimated for each country and can change over time. It is calculated as the maximum of 1.5 times the initial yield and the value of an external user-controlled parameter (***ylmax***).

Finalizing computation of yield. Given the basic yield (*BYl*), a check is made to see if its annual growth is within reason. Specifically, *BYl* is not allowed to exceed its moving average times a bounding growth rate (*YlGrBound*). This bound is the maximum of a user-controlled global parameter (***ylmaxgr***) and an initial country-specific target growth rate linked to food demand growth, adjusted upward if the user is forcing up agricultural investment with an exogenous multiplier (***aginvm***). At this point, the basic yield is adjusted by four factors to compute the final yield. The first three adjustments are fairly simple.

The first adjustment can represent either price changes or changes in profit levels associated with such changes. Farmers quickly respond to these variables in their intensity of cultivation via factors such as fertilizer usage levels or somewhat more extensive use of their cropland (e.g., planting fence to fence). Because of the computational sequence, prices lag one year, but food stocks, on which those prices are based, are available information in each year of the recursive calculation. Hence we compute a country-specific stock adjustment factor (*StockAdjustmentFactor*) as a second multiplier on basic yield (that multiplier extends to the country level the earlier global stock's impact on technological advance). Calculation uses the *ADJSTR* function level (the PID function described in Section 6.1.4.3's discussion of the economic model) and the current stocks, the recent change in stocks, and a desired stock. The desired stock level is given as a fraction of the sum of crop demand and crop production. The focus in IFs on yield response to stocks differs somewhat from the common use of price elasticities of supply. (For reference, Rosegrant et al., 1995, 5 report that price elasticities for crops are quite small, in the range of 0.05 to 0.4.)

$$YL_r = BYL_r * StockAdjustmentFactor_{r,f=1}\,(\boldsymbol{elfdpr1}, \boldsymbol{elfdpr2}) * EnvYlChg_{r,t-1}/100 * \boldsymbol{ylm}_r$$

The second adjustment is for changes in the balance between irrigated and non-irrigated land (as calculated by the water model). Irrigated land globally is about 2.35 times as productive as non-irrigated land, and changes in aggregated yield are made as land-use changes (based on data in Evans and John Sadler, 2008).

The third and simplest adjustment is a country-specific user-controlled multiplier (***ylm***), a parameter for quick and direct control of yields. In scenario analysis, it can represent any yield-impacting factors that are not in the model, including severe weather events or technological breakthroughs.

The fourth adjustment is more complex and represents the potential effects of a changing climate on crop yields (*EnvYlChg*), lagged by one year. It has two multiplicative terms: (a) the direct (and positive) fertilization effect of atmospheric carbon dioxide concentrations and (b) the effects (which could be positive or negative) of changes in temperature and precipitation.

The direct effect of atmospheric carbon dioxide assumes a linear relationship between changes in the atmospheric concentration from a base year of 1990 and the percentage change in crop yields.

$$CO2Fert_{t+1} = \boldsymbol{envco2fert} * \left(\frac{CO2PPM - CO2PPM_{t=1990}}{CO2PPM_{t=1990}} \right) * 100$$

where

envco2fert is a global user-controllable parameter
$\text{CO2PPM}_{t=1990}$ is hard coded as 354.19 ppm

The effects of changes in annual average temperature and precipitation build on the work of Cline (2007) and Parry et al. (2004) and are based upon two assumptions: (1) there is an optimal temperature (*Topt*) for crop growth, with yields falling both below and above this temperature and (2) there is a logarithmic relationship between precipitation and crop yields. Work reviewed in Cline (2007) informed the choice of this functional form and parameterization. Together, changes in temperature and precipitation result in the following equation:

$$ClimateEffect_t =$$

$$100 * \left\{ \frac{e^{-0.5 * \frac{(T0_r + DeltaT_r - Topt)^2}{SigmaTsqd}} * \ln\left(P0_r * \left(\frac{DeltaP_r}{100} + 1 \right) \right)}{e^{-0.5 * \frac{(T0_r - Topt)^2}{SigmaTsqd}} * \ln(P0_r)} - 1 \right\}$$

where

*T*0 and *P*0 are country-specific annual average temperature (degrees C) and precipitation (mm/year) for the period 1980–1999
DeltaT and *DeltaP* are country-specific changes in annual average temperature (degrees C) and precipitation (percent) compared to the period 1980–1999. These are tied to global average temperature changes and described in the documentation of the IFs environment model
Topt is the change in average annual temperature from the 1980–1999 value at which yield is maximized. It is hard coded with a value of 0.602 °C
SigmaTsqd is a unitless shape parameter determining how quickly yields decline when the temperature moves away from the optimum. It is hard coded with a value of 309.809

Given the two climate factors, the combined environmentally induced change in yield is the product of them.

$$EnvYlChg_{r,t} = \left(\left(\frac{CO2Fert_t}{100} + 1 \right) * \left(\frac{ClimateEffect_t}{100} + 1 \right) - 1 \right) * 100$$

There are two final checks on crop yields. They are not allowed to be less than one-fifth of the estimate of basic yield (*BYl*) and they cannot exceed a parametric maximum (***ylmax***). Currently that maximum is 100 tons per hectare, a level of production that would be highly unusual and would represent something like sugarcane production in a tropical climate (e.g., in Mauritius).

Meat and fish production. IFs represents meat and fish production more simply than crop production. Meat production, which includes milk and eggs, is the product of livestock herd size (represented in metric tons) and an exogenously controlled slaughter/production rate (***slr***). The herd size changes over time in response to global and domestic meat stocks. The livestock herd is supported by grazing land as possible and otherwise by feed from crops.

Fish production has two components: wild catch (*AGFISHCATCH*) and aquaculture (*AQUACUL*). Wild catch builds on a data-based initial value and an exogenous multiplier (***fishcatchm***). Aquaculture is assumed to grow at country-specific rates tied to past experience (***aquaculgr***), but moving to zero over time with saturation in potential; a multiplier can also be used to increase or decrease aquaculture production (***aquaculm***).

7.1.4.2 Other Important Functions, Including Demand and Equilibration

Demand and prices. Effective demand for food is represented first in terms of calories per capita, and second in terms of grams of protein per capita. IFs uses a cross-sectionally estimated function with GDP per capita at PPP to determine the typical level of demand, adjusted by shift factors reflecting each country's historical pattern and by response to changes in world crop prices. Conversion factors transform calorie and protein demand into food demand in metric tons and allocate it across crops, meat, and fish, with shifts from crops to meat and fish with income increase (taking into account country differences that can reflect cultural patterns). Parameters allow scenario analysis of the portion of calories consumed from meat (***calmeatm***) and the maximum level of meat consumption (***meatmax***). The model fills effective demand for crops, meat, and fish under the assumption that food supplies will ultimately be available if income-based and price-adjusted demand is there. Inventory stocks will be run down or built up.

Prices equilibrate supply and demand as in the economic model (with a feedback to calorie demand), using the *ADJUSTR* function (PID controller) of IFs to change prices (see Section 6.1.4.1). The process compares not just the absolute gap between food stocks and desired levels, but also the direction and magnitude of annual change.

Undernutrition. Shortages of calories relative to nutritionally needed levels are a primary driver of child undernutrition. However, children suffer from undernutrition not just because of inadequate intake; often they suffer because unsafe water and sanitation lead to diarrheal disease and the inability of their bodies to use calories. Thus the IFs formulation ties undernutrition both to average calories and to the portion of the population without access to piped water supply. Severe acute malnutrition is a function also of political instability.

Investment. While determination of demand for agricultural investment is a fairly complex process in IFs, it is driven in the long run primarily by changes in the ratio of agricultural demand to GDP and by GDP growth and adjusted in the shorter term by both world and domestic food stocks. Behavior is smoothed to avoid large overshoots of change in either direction. The demand is taken to the economic model and normalized with other investment demands to determine supply of investment for agriculture.

When that investment is brought back into the agriculture model, it has two possible targets. The first is capital stock, and the second is land. The split between the two destinations reflects the relative returns to cropland development and agricultural capital (e.g., equipment and buildings), the latter of which is determined by the increased yield that could be expected from an additional unit of agricultural capital. The costs of developing cropland increase as potential increments decline.

Land. Beyond cropland's response to investment, changes in land use have an algorithmic structure to maintain accounting across land types. First, changes in urban land respond to changes in average income and population, and urban land increases draw from all other land types. Second, cropland development requires changes in forest and "other" land. Third, changes in grazing land are a function of average income, with shifts again being compensated by changes in forest and "other" land. Finally, conservation policies (or overuse) introduced by an exogenous multiplier can influence the amount of forestland, with any necessary adjustments coming from crop and grazing land. Net change in forest area has a direct linkage to carbon emissions, as discussed later in this chapter.

7.1.4.3 Relationship of Physical and Value Representations of Agriculture

There are several places where connections exist between the physical variables of the agriculture model and the currency value variables of the economic model. For the most part, the physical model is considered to be the dominant representation of agriculture, and its values override those that would otherwise be computed (or are computed on a preliminary basis) in the economic model. Capital and labor, however, are constrained by the larger economy's allocation of them.

Variables with both physical and currency values and/or connections in the agriculture model, and their treatment, are:

Trade. The physical values of agricultural exports and imports are translated to currency values by using world agricultural prices. Values of trade reflect the specific food elements within the aggregate IFs crop, meat, and fish categories. An adjustment or shift factor represents the initial year's ratio of physical to currency values.

Agricultural consumption. The volume in the agriculture model, again adjusted by world prices and initial-year ratios, provides food consumption in value terms for the economic model (subject to a constraint of 85% of total national consumption expenditures being on food).

Food stocks. The physical value of stocks is converted by world prices and taken to the economic model.

Food prices. Variations in country-specific relative prices from the world price are taken to the economic model.

Investment by destination. The demand for agricultural investment is taken to the economic model in currency value terms. After the economic model determines actual availability, that investment comes back for direction into land and agricultural capital.

Labor. The economic model determines agricultural labor supply.

7.1.4.4 Limitations

The IFs agricultural model represents land and associated crop and grazing potential by country or, in select cases, by smaller geopolitical units, but not on a global grid. Similarly, the climate-change feedback to yield lacks grid-level detail. The aggregation of all crops, meat, and fish into those three high level categories is also limiting.

Although representation of land-use, irrigation potential, and technological change trends provide physical underpinnings for understanding production cost, and therefore price change over time, the model does not represent soil quality and degradation. In general, the determination of food prices in the equilibration structure, while indicative, must also be understood to be tentative.

And finally, many of the parameters in the IFs agriculture model (and other models) rely on other studies, stylized facts, and qualitative estimates. This can, of course, be a strength as well as a weakness because there is value in building on what others have learned.

7.1.5 Comparative Scenarios

The Food and Agriculture Organization of the United Nations periodically produces projections of world and regional agricultural demand and production. In its 2012 revision, the core FAO expectation was that global demand for all agricultural commodities will grow by 1.4% annually from 2005/2007 through 2030, then by 0.8% through 2050 (Alexandratos and Bruinsma, 2012, p. 64). These numbers continue a slowing already evident in recent years due to factors such as diminishing population growth and saturation of calorie needs in an increasing number of countries. Gouel and Guimbard (2017) anticipated that global calorie demand will grow by 46% from 2010 to 2050, less than half the growth rate of the preceding four decades.

Fig. 7.3 shows the IFs Base Case scenario values of total calorie demand (as measured by per capita availability times population) through 2100 for countries across World Bank income category country groupings. On a global basis, the growth rate from 2014 through 2030 is 1.2% and that from 2030 through 2050 is 0.74%, slightly less than the FAO numbers; the differences probably reflect the supply side constraints in IFs. Total calorie demand growth between 2015 and 2050 in the IFs Base Case is 47%. There is an overall S-shaped pattern between 1965 and 2100, with very slow growth after 2050. The figure also makes clear the major shift in sources of the demand, from the rapid growth in recent decades in upper-middle-income countries, dominated by China, to lower-middle-income countries, heavily influenced by India, but including also Bangladesh, Indonesia, Nigeria, and Pakistan, followed in turn by growth in low-income countries. Given the historical pattern of most food demand being satisfied by local production rather than trade, the pressure for increased production in these countries is apparent.

At the global level, forecasts of growth by the FAO and IFs on the food production side are, of course, nearly identical to those for demand. For the most part, the variations in crop production forecasts for 2030 across FAO, IMPACT, LEITAP/MAGNET, and IFs are not great (see Figure 4.2.1.2 in Stehfest et al., 2014, p. 116 for some cross-model comparison).

Land-use projections can explain some of the differences in these and other production expectations. IFs and some other models suggest that net deforestation is slowing and may largely cease before mid-century as continued growth in yields outpaces demand growth; for example, see van Vuuren and Kok (2012, p. 117). Also, the Organisation for Economic Co-operation and Development (OECD) anticipated in its baseline scenario that land

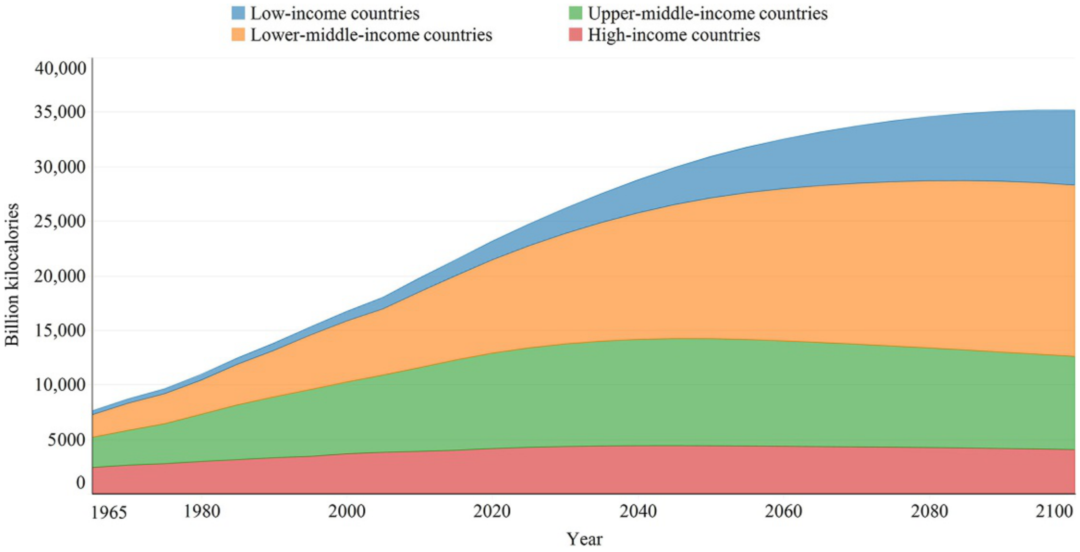

FIG. 7.3 Total calories available by country economy classification: History and IFs Base Case scenario to 2100. *Notes: Uses World Bank classifications based on gross national income per capita; values are available calories per capita times population.*
Source: IFs Version 7.36; historical data from the Food and Agriculture Organization of the United Nations.

devoted to agriculture will peak before 2030 (OECD, 2012). In the IFs Base Case, global cropland rises by only about 60 million hectares through mid-century, then slowly declines toward early century values (with forest area then rising). (IFs does not distinguish plantation forest area from natural primary or secondary growth as some models do, and the former has been growing steadily.)

In contrast, representation of the Middle of the Road SSP2 scenarios for land use across five IAMs (see Section 3.3.2.1 on the SSPs) showed a growth in global cropland from somewhat more than 1500 million hectares in 2005 (varying by model and scenario represented) to about 1800 in 2060, and then either stabilization or more modest growth through century end.[16] In SSP2, a project using IMAGE projected an increase of 260 million hectares of cropland for food and energy by 2050, with an associated decrease of about 250 million hectares of forest area (United Nations Convention to Combat Desertification, 2017, pp. 111–12). Uncertainty around future land use is by far the greatest in Africa.

Scenarios around change in crop yield have displayed significant variation. van Vuuren and Kok (2012, p. 133) pointed to a range in other studies from 0.67 to more than 1% in average annual growth rates of cereal yields between 2010 and 2050, and reported their own Trend scenario value just below the lower end of that range. The value in their Global Technology pathway scenario was about 1.25%, and that in their Consumption Change pathway scenario was about 0.8%. In IFs, the Base Case scenario rate for aggregate crop yield growth is 0.63%

[16] Across all SSPs, the model values ranged from modest decline in cropland by 2100 to growth by 700 million hectares in AIM/CGE (NIES) for SSP3 (Riahi et al., 2017, Abstract).

between 2015 and 2050. For the FAO, Alexandratos and Bruinsma (2012, p. 121) showed 0.68% for cereals and 0.77% for all crops from 2005/2007 to 2050 (with 0.018% increase in cereal land and 0.021% in total crop area). Assumptions about technological advance (including adoption by followers) and about policy choices are interacting variables that explain much of the uncertainty around crop yield forecasts.

Although we have focused on production as the dominant source of uncertainty (especially around yield, given limited cropland expansion globally), the major interest that lies behind our agricultural modeling remains the satisfaction of nutritional needs. We saw in Fig. 7.1 the historical pattern of growth in available calories for countries at different current income levels. Our IFs Base Case projects a continuation of that process, anticipating that in 2050 the average per person available kilocalories per day will be 3230 globally (up from 2900 in 2015), with 3660 per person in OECD countries and 3160 per person in the non-OECD (mostly developing) countries. The global values projected by the FAO (Alexandratos and Bruinsma, 2012, pp. 20–22) were 3070 in 2050, up from 2860 in 2015 (and reaching 3200 in 2080), and its 2050 projections for developed and developing countries, respectively, were 3490 and 3000. The IFs values are obviously somewhat higher in spite of somewhat lower crop yield growth expectations.[17] As indicated in the discussion of production forecasting, one complication in making projections of calorie availability is the great variation of calorie content in different crops. The aggregation of all crops by IFs implicitly assumes constant country-specific patterns of crop mix, which will not be the reality; the implications of changes in crop mix for calorie availability is uncertain.

Scenarios around undernutrition depend not just on average calorie intake within countries but also on its distribution and potentially, as in IFs, on interacting variables such as the safety of drinking water (because diarrhea can prevent the effective use of food consumed). In spite of the continued expected growth in calorie availability around the world, the IFs Base Case scenario suggests that in 2050 there will still be more than 300 million people (3% of the global total) who are undernourished, down from somewhat fewer than 800 million and 11% in 2015 (numbers very comparable to the Trend scenario of van Vuuren and Kok (2012, p. 114) and the FAO projection for 2050 of a similar 318 million (Alexandratos and Bruinsma, 2012, p. 6). The IFs Base Case global level in 2030 is more than 6%, with about 100 countries at or more than the 3% target of the Sustainable Development Goals (SDGs).

Undernutrition of children draws special attention in modeling because of its life-long effects and because childhood weight-for-age is the most common and heavily sampled measure of undernutrition, making such assessment easier than it is for adults. Fig. 7.4 shows global numbers of undernourished children from the full set of SSP scenarios, which, as reproduced within IFs, allow the computation of undernutrition. In all five scenarios, the

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[17] van Vuuren and Kok (2012, p. 124) show a figure that suggests a global consumption of about 7×10^{15} kilocalories per year in 2010, rising to about 11.5×10^{15} kilocalories in 2050 in their Trend scenario (about a 64% total increase). IFs version 7.23 showed a 55% increase in the same period. Obviously, world population increases would be somewhat different in the two sources, and estimating numbers from a graphic is subject to error, making this comparison a crude one.

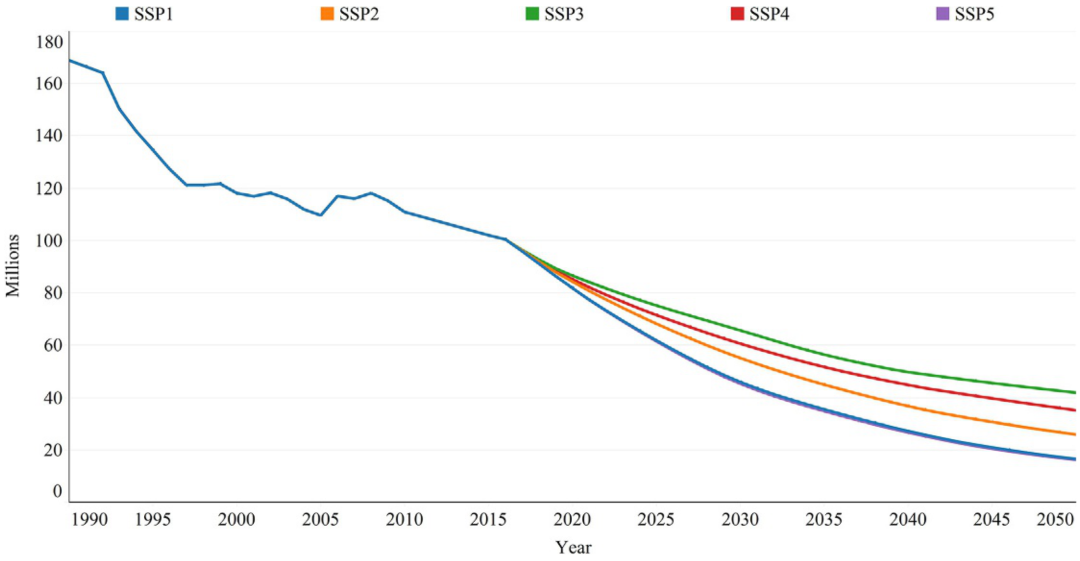

FIG. 7.4 **Undernourished children globally: History and IFs SSP-based scenarios to 2050.**
Source: IFs Version 7.36; SSPs replicated in IFs by exogenously introducing demographic variables, GDP growth, and adult educational attainment from sources described in "Supplementary Note for the SSP Data Set" at https://tntcat.iiasa.ac.at/SspDb/static/download/ssp_suplementary%20text.pdf, and income distribution assumptions tied to van der Mensbrugghe (undated). Historical data are from the World Bank's World Development Indicators, using interpolation to fill holes and removing 2011–2014 because of incomplete data.

numbers and percentages decline from the 2015 level of about 100 million children and 15% (a higher rate than for the total population). In 2050, the range across scenarios is from four to 25 million and from 2.7 to 5.5%. The UN's Millennium Ecosystem Assessment produced the only comparable projections of which I am aware, with values in 2050 ranging from more than 60 million (Global Orchestration) to 180 million (Order from Strength); see Millennium Ecosystem Assessment (2005, p. 81). The greater optimism of the IFs analysis suggests the pattern of improvement in recent years.

7.2 ENERGY

Energy is the second major bridging system between humans and the environment. As in modeling of agriculture, while the demand side may drive the model, the key dynamic uncertainties to explore in the long term are on the supply side, especially the mix of energy sources. Across the rest of this century, energy demand will increase because of the growth of the global economy (around 3% annually in the IFs Base Case) but rise more slowly than GDP because of increases in energy efficiency (reducing annual energy demand growth by 1% or more relative to economic growth in the IFs Base Case). Such a scenario will be wrong, of course, but is unlikely to be dramatically in error.

On the supply side, as noted earlier, the uncertainties are great. In little more than two centuries we have experienced dramatic transitions, from being a species fueled predominately by recently living biomass (with food for our bodies and wood for our cooking and warmth) to one fueled predominantly by fossil biomass (with peat and coal dominating initially, followed by oil and natural gas). There is debate (see Section 7.2.5) as to whether we will remain mostly fossil fuel-based throughout the current century or move predominantly to renewable sources in that time, using sun power without biomass intermediation (or even emulating the sun's generation of power via fusion).

7.2.1 Concepts, Structures, and Data

Coal is plentiful globally and could support human energy needs through the century. Its large-scale combustion emits massive quantities of particulates and gases, harmful to humans and the broader environment. With technology for sequestration of carbon dioxide emissions still in its infancy and expensive, it appears very possible that other fossil fuels and new renewable energy forms will prevent coal from playing that dominant role.

Oil and gas, while much cleaner and abundant, are not readily available in the same huge quantities. The McKelvey box (Fig. 7.5) helps us conceptualize resource magnitudes, the stocks from which annual production may ultimately flow (McKelvey, 1972). Reserves are discovered resources, known to be commercially producible. For 2016, British Petroleum (BP) estimated global reserves for coal at 4203 billion barrels of oil equivalent (BBOE), those for oil at 1706 BBOE, and those for natural gas at 1146 BBOE.[18] Contingent and prospective resources of each tend to be much greater than reserves. The Federal Institute for Geosciences

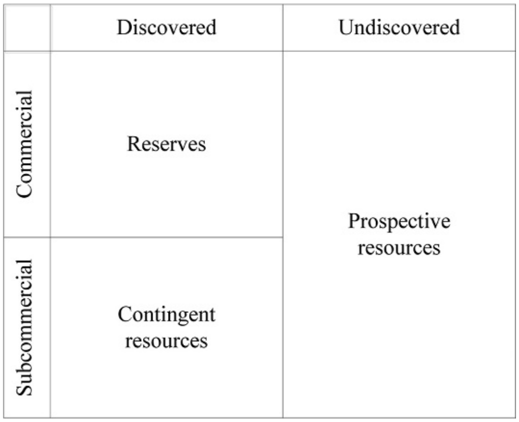

FIG. 7.5 McKelvey box representing categories of geological resources.
Note: See McKelvey (1972) and Rogner et al. (2012) for conceptual discussion and elaborated representations.
Source: IFs project simplified representation.

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[18] Calculations of author based on reserve data from the June 2017 *BP Statistical Review of World Energy* at https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf.

and Natural Resources (BGR) in Hannover, Germany estimated that in 2015 ultimate resources of coal were 94,760 BBOE; those of conventional oil were 4014 BBOE, with shale resources more than 10 times that, and those of gas were estimated at 5121 BBOE, with shale resources at 36 times that level (Federal Institute for Geosciences and Natural Resources, 2016). But, much of that will never be discovered. Further, much that is discovered will prove uneconomical to produce, especially in light of falling prices of renewable energy forms and increasing movement to internalize at least some of the environmental impacts of fossil fuels into the prices faced by their users.

Cumulative global production across time will not exceed some potentially quite small fraction of the ultimate fossil resource base. Given estimates of that ultimately recoverable resource portion, estimates of the maximum pattern of annual production across time are also possible, and most rely on the Hubbert's (or Hubbert) curve. That curve is bell-shaped, conceptualized as the sum of the rise and fall of production in individual oil wells and fields. Using estimates of renewable conventional oil resources, M. King Hubbert (1956) famously forecast the ultimate production pattern and total for the contiguous 48 US states, and Fig. 7.6 matches his curve with subsequent production data. Those fit remarkably well through 2010 and then diverged because of access to unconventional oil sources with new technology.

There is great debate about the ultimately recoverable global resource levels of oil and natural gas, but none about their being finite. Projections of peaks in global production range

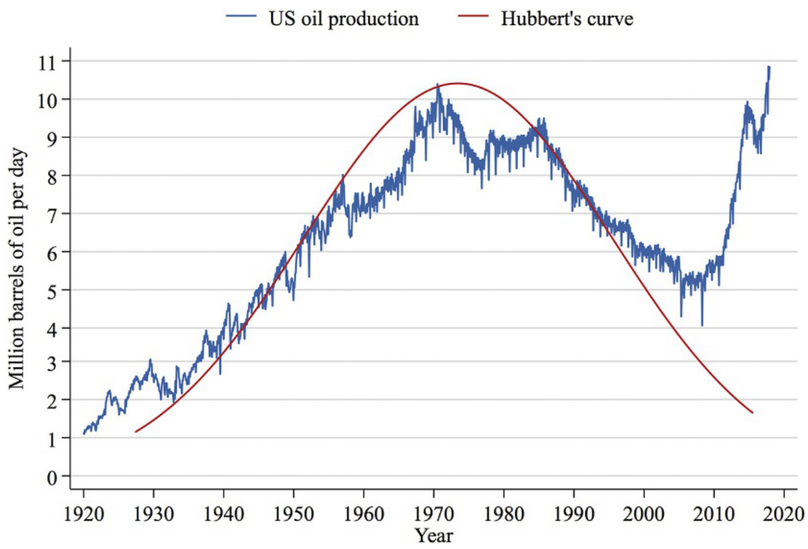

FIG. 7.6 **Hubbert curve and historical US crude oil production from 1920 to 2018.**
Note: Contiguous 48-state oil production only; production by month.
Source: IFs Project; patterned after figure from Wikimedia Commons by RockyMtnGuy available through a CC BY-SA 3.0 license at https://commons.wikimedia.org/wiki/File:US_Crude_Oil_Production_versus_Hubbert_Curve.png; uses data from the U.S. Energy Information Agency at https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPUS1&f=M.

fairly widely, but many fall, roughly, into a period around 2030.[19] Increasingly, however, the heavy competition that renewables give fossil energy has led analysts to talk about peak demand rather than peak production.

Clearly, there is strong motivation to represent projections of energy in stock and flow terms, something like McKelvey boxes of stocks, and Hubbert's curves of flows. A stock and flow approach also allows the user to easily change initial recoverable resource stock assumptions in order to produce alternative scenarios of flows. Not all models, including the linear programming approach of MESSAGE (discussed in Section 7.2.3) take that approach, however; it is also possible to represent a supply curve more simply with costs that rise with cumulative production but also potentially fall because of technological advance.

As in other model issue areas (the primary exception being demography), energy data in the early years of world modeling were very scarce. A very important early source was Darmstadter et al. (1971), still of interest because it provided massive amounts of production, consumption, and trade data as far back as 1925. The most substantial single contemporary source of data is the International Energy Agency (IEA), which provides extensive coverage of production, consumption, and trade. British Petroleum's annual *Statistical Review of World Energy* is also very helpful (and available without cost). Neither source, however, is very helpful with respect to ultimate resource estimates. For that, one can tap the US Geological Survey. In recent years, however, estimates with regular updates from the BGR have become especially useful, including in differentiating more and less conventional resource bases.[20]

7.2.2 Energy Transitions

The Hubbert's curve, and the McKelvey box portrayal of resource availability that serves as its foundation, already identify one of the energy system transformations that underlies most long-term analysis—namely, the all-but-certain peaking of global production of oil and natural gas in this century. We know, of course, that the peaking relates not to the total exhaustion of resources, but to the relationship between the upward pressure that resource depletion will put on costs of those fossil fuels (even as improved technology works against that pressure and sometimes more than offsets it), the availability and costs of alternative energy forms, and policy choices.

The forces of resource limits and changing technology have undergirded the major global energy transitions noted earlier, most especially over the last two centuries. Throughout most of the 19th century, biomatter (including wood) remained our major energy source, but coal played that role in the first half of the 20th century (see Fig. 7.7). Oil production and consumption exploded in the second half of that century, but natural gas has followed, even while coal's absolute contribution has also continued to grow, albeit more modestly.

Costs of energy from wind and solar have been falling steadily and quite dramatically in recent decades, undergirding the rise of new renewable energy sources, especially in electricity production. Fig. 7.8 traces the global sources of electricity generation since the early 1960s

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[19] The United States Government Accountability Office (2007) reviewed a wide range of estimates even before the major surge in unconventional oil and gas production.

[20] Other less frequently used sources are available. According to Stehfest et al. (2014, p. 101), the TIMER project drew upon Mulders et al. (2006) and Rogner (1997) for estimates of resources; see also Rogner et al. (2012).

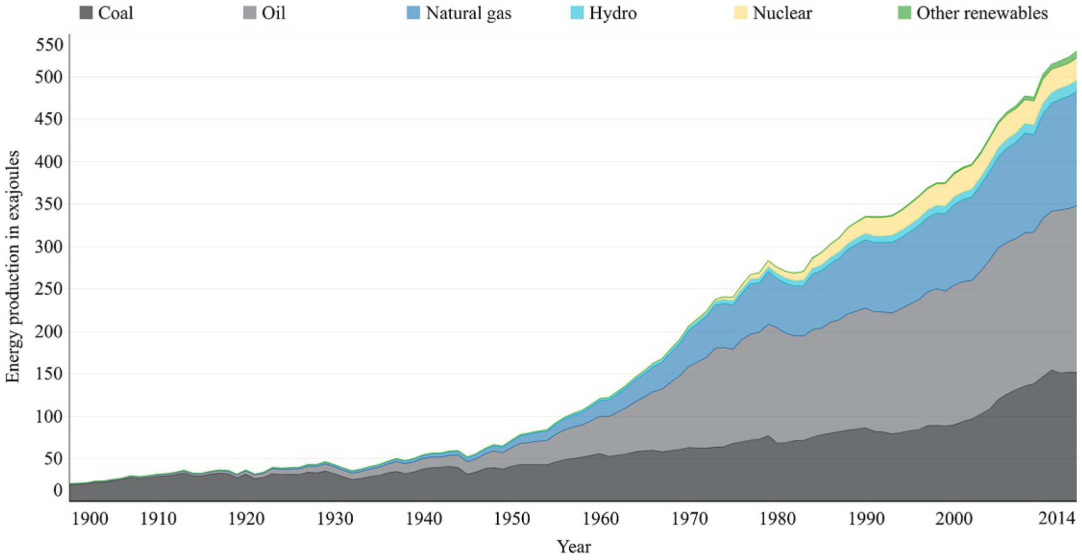

FIG. 7.7 Global primary energy production by source from 1900 to 2014.
Note: Patterned after a figure previously available at Our World in Data (ourworldindata.org) through a CC BY-SA 3.0 license. Source: IFs project, using data from the US Energy Information Administration via the Shift Project data portal (www.tsp-data-portal.org) available through a CC BY-SA 3.0 license.

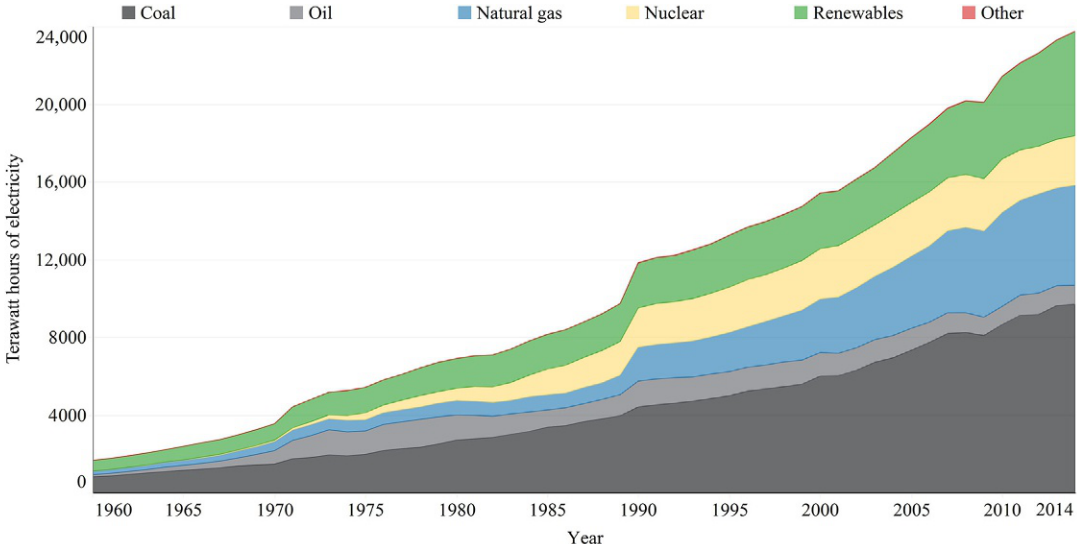

FIG. 7.8 Global transition in sources of electricity production from 1960 to 2014.
Note: Values are in Terawatt hours (TWh) of electricity. Transient in 1990 reflects addition of former Soviet Union countries. Source: IFs Version 7.36, using data from the International Energy Agency.

and shows that renewables (including hydropower as well as newer forms) are competing with natural gas as the second source after coal. In fact, the IEA suggested in its 2018 *World Energy Outlook* that renewable sources have overtaken natural gas, producing 25% of electricity in 2017, and will challenge coal by 2040, producing 33% of electricity with a Current Polices scenario and 41% in a New Policies scenario (IEA, 2018, pp. 526–529). Renewable sources as a share of total energy demand rise from 15% to 17% by 2040 with Current Policies and 20% with New Policies (which IEA considers its medium scenario).

There is, however, tremendous uncertainty concerning the energy mix of the future. Coal with carbon capture and storage could emerge as a competitive and clean technology, as could new versions of nuclear energy. Cost floors for new renewables are largely unknown, as is society's willingness to subsidize those forms.

Heavy focus on the supply side should not, however, lead us to downplay the demand side of the energy system. Whereas great efficiency is not likely to be gained in human use of food (although meat consumption could drop, allowing crop calories to feed more people, and current substantial levels of food waste could be reduced), there is much to be expected with respect to the economy's use of energy. For most of the fossil-fuel era, the use of energy rose in near lockstep with the growth of GDP. However, that relationship broke in the 1970s. Between 1990 and 2014, the use of energy per dollar of GDP in high-income countries declined by 1.4% annually (see Fig. 7.9). In upper-middle-income, lower-middle-income, and low-income counties, the declines were 1.5, 2.3, and 1.0%, respectively. Fig. 7.9 includes biomass, however, and the picture without it is very different, especially for low-income countries where biomass use is very high. Looking only at more modern energy forms, the ratio of energy demand to GDP in low-income countries is now almost identical to that of high-income

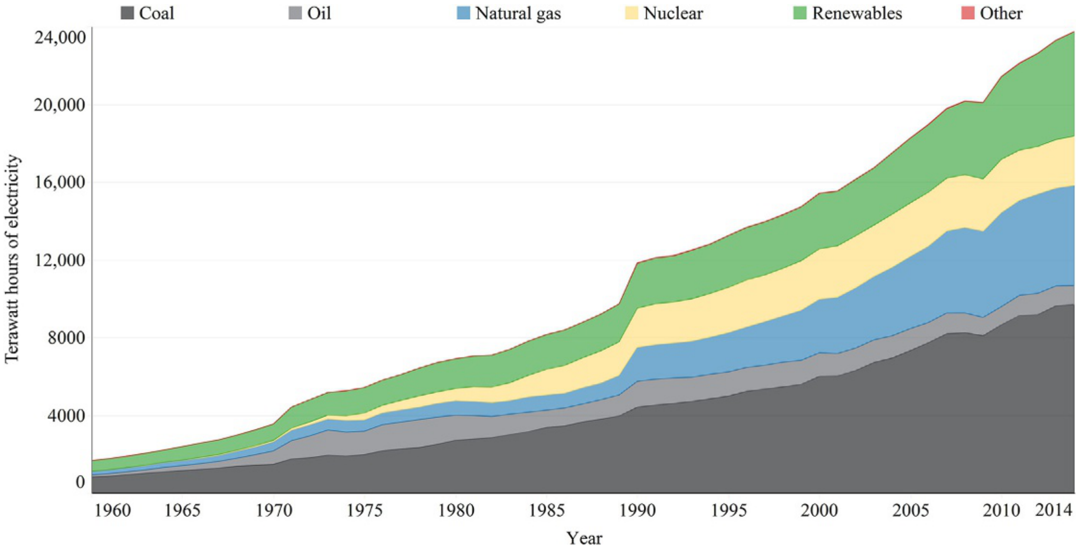

FIG. 7.9 **Energy use per unit of GDP by country economy classification from 1990 to 2014.**
Note: *Uses World Bank classifications based on gross national income per capita. Values are in barrels of oil equivalent (BOE) per $1000 of GDP.*
Source: IFs Version 7.36, using data from the International Energy Agency.

countries, and efficiency has improved at 3.5% annually. In the future we can expect continued gains, especially in the upper-middle-income countries where the large industrial push by China has slowed such gains in recent decades. Lovins (1985) coined the term "negawatt" to describe such energy savings. In conclusion, even as we focus much attention on supply, we must look carefully also at the uncertainties in energy demand.

7.2.3 Modeling Energy

Although it is simply not possible to review the wide range of global energy models now extant, Krey (2014) reviewed the field of energy-climate modeling in terms of general structural concerns. Krey also pointed to other reviews of such models, including those of the Energy Modeling Forum and AMPERE.

Among the best-known energy models are TIMER of the IMAGE system at PBL Netherlands Environmental Assessment Agency, MESSAGE from IIASA, and the World Energy Model system of the International Energy Agency. TIMER (TARGETS IMage Energy Regional model) is a dynamic recursive partial equilibrium system for 26 world regions with projections to 2100 (Stehfest et al., 2014, pp. 71–106). The demand side largely drives the model, and separately represents industry, transport, residential, public and private services, and other (mostly agriculture) users. TIMER represents efficiency improvements; some improvements are directly responsive to prices and some to other factors, such as technological change. The supply side represents multiple resource categories (e.g., conventional and unconventional) for oil, gas, coal, and nuclear fuels, costs for bioenergy from feedstocks of it, and costs for other renewable forms from production sites. Learning by doing reduces supply costs, but growth in cumulative fossil fuel production, and therefore depletion of scarce resources, increases them. Prices reflect costs. Primary supply feeds secondary supply (or energy carriers), namely electricity or hydrogen, both of which require investment. Demand is always met with domestic or imported supply, with trade responding to price differentials.

Like TIMER, the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) is part of a larger integrated modeling system (McCollum, 2012),[21] soft linked to MACRO[22] on the economic side and to the MAGICC[23] global climate model. MESSAGE (see also Section 3.2.2) represents the world in 11 regions from 1990 to 2110 in five- and 10-year time steps. It is an energy engineering model in a linear programming environment, and as such it optimizes energy delivery with lowest cost (with a variety of specifiable constraints and cost coefficients) to satisfy the demand of six end-use categories in industrial, residential, commercial, and transportation sectors across its time horizon. It is also usable myopically with optimization by time period instead of intertemporally. MESSAGE selects a supply portfolio that draws on a very wide range of conventional and nonconventional primary, secondary, and end-use technologies, including biomass, wind, solar, geothermal, carbon capture and storage, hydrogen, and electrified transport (but not

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[21] See documentation for MESSAGE at https://wiki.ucl.ac.uk/display/ADVIAM/Model+concept%2C+solver+and+details+-+MESSAGE.

[22] See https://wiki.ucl.ac.uk/display/ADVIAM/Macro-economy+-+MESSAGE for description of MESSAGE and MACRO linkage.

[23] MAGICC is documented at http://www.magicc.org/.

fusion or geo-engineering). Supply cost curves are a function of cumulative production, and the system does not explicitly represent resource depletion. Technology change on the supply side is generally exogenous via cost assumptions.[24] For example, assumptions for cost reductions in different non-biomass renewable technologies vary from 18% to 70% in the SSP2 scenario (Fricko et al., 2017). Exogenous scenarios provide energy service demands, and therefore implicitly represent changing efficiencies (a distal factor); prices adjust demand endogenously (a proximate factor).[25]

The International Energy Agency uses the World Energy Model (WEM), documented in IEA (2015), to produce its annual *World Energy Outlook* series (for example, see IEA, 2017). WEM represents energy demand in 25 world regions (of which 12 are individual countries), models oil and gas supply in 120 countries/regions and coal in 31, and projects through 2040. Similar to TIMER, it represents demand by industry: non-energy use (e.g., plastics), transport, residential, services, and agriculture. Demand equations include price responsiveness, and WEM represents considerable detail in each demand sector, including potential for efficiency improvements. Primary energy types are coal, oil, gas, nuclear, hydro, bioenergy, and other renewables. Secondary processing includes coal upgrading, refining, heat production, and biomass processing as well as power generation. The model is written in the Vensim systems dynamics language and it relies on investment flows to build capital stocks on both demand and supply sides. Oil and gas production and cost projections in WEM are built from the bottom up, using field-based past patterns with estimates of reserves and resources that draw heavily on analyses of the US Geological Survey. Coal supply combines the resource approach with market analysis, and bioenergy supply looks to biomass analysis by the FAO and IIASA. Prices equilibrate supply and demand in each time step by iteratively changing them so as to engender sufficient investment (assumed to be immediately available) to balance them. Once again, the demand side drives WEM and there is considerable uncertainty, but the greatest uncertainties are on the supply side.

7.2.4 Energy in IFs

As with agriculture, IFs integrates its physical partial equilibrium model with its general equilibrium economic model (similar to what MESSAGE also does), gaining the benefits of enhancing the energy sector in the economic model and accounting for factors of production in the energy model. Further, carbon emissions from energy (influenced by possible carbon taxes) link to greenhouse emissions (discussed later in this chapter).

The IFs energy model endogenously represents both changes to reserves and remaining resources (initialized exogenously) and production of oil, natural gas, coal, hydroelectric power, nuclear power, and new/other renewables. Assuming high substitutability of energy forms over time, it represents demand, trade, and price of energy in the aggregate. The IFs energy model does not distinguish among final energy demand categories (e.g., manufacturing versus residential). Nor does it build in intermediate or processed energy forms, notably

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[24] MERGE was one of the earliest energy models to represent technological change endogenously, as a function of cumulative capacity. It followed even earlier efforts in POLES, PRIMES, and MARKAL (Kypreos and Bahn, 2003, p. 249).

[25] See discussion of energy service demands in MESSAGE at https://wiki.ucl.ac.uk/display/ADVIAM/Demand+-+MESSAGE.

electricity and gasoline (and potentially hydrogen), in spite of the IFs infrastructure model's forecast of electricity access. Thus its treatment of energy is focused on the supply side and on primary sources, and its demand is actually gross or primary demand (primary supply adjusted by trade) rather than final demand with supply reduced by losses in conversion (e.g., losses of the energy in oil, gas, and coal when they are burned to create electricity).

As with agriculture, given population and income forecasts from the respective models in IFs, energy demand is relatively less uncertain and complicated to represent than the production shares of energy types. We therefore give most attention to supply. For full model documentation, see http://pardee.du.edu/wiki/Main_Page.

7.2.4.1 Resources and Production

Modern energy production is very capital and technology intensive. In the IFs energy production function, only capital and the ability of capital to generate output (the capital-to-output ratio) are treated as factors of production (not labor or land, as in the economic or agriculture models). Energy production (*ENP*) is initially estimated by dividing the capital in each energy category (*KEn*) by the appropriate capital-to-output ratio (*QE*).[26] An exogenous multiplier, ***enpm***, can increase or decrease production.

$$ENP_{r,e} = \frac{KEn_{r.e}}{QE_{r,e}} * \boldsymbol{enpm_{r,e}}$$

The dynamics of the capital-to-output ratios and of capital formation via investment thus become central to understanding production. The two interacting factors that determine the capital-to-output ratios in IFs are technological advance and resource exhaustion.

Technological advance and basic capital-to-output ratios. All energy types begin with basic capital-to-output ratios (*BQe*). These evolve over time according to exogenous assumptions about technological advance (***etechadv***) for each energy type, resulting in declining capital required for each unit of energy produced.

$$BQe_{r,e,t} = BQe_{r,e,t-1} * (1 - \boldsymbol{etechadv}_e)$$

The translation of this basic capital-to-output ratio to the value used to determine energy production (*QE*) varies by energy type and the nature of resource constraints, if any, on the production.

Resource base. The resource constraints associated with fossil fuel energy production enter IFs in two ways. First, for fossil fuels there is a direct restraint on production from the level of known reserves. For instance, extraction from fields of more than about 10% of remaining oil each year can damage the ability to maximize long-term production. IFs represents the discovery process that increments reserves over time (responsive to initial trends and prices, but subject to the limit of ultimate resources), decrements reserves each year with production, and uses a reserve-to-production ratio maximum to limit annual production if it bumps up against that ratio.

For oil and gas, IFs computes an ultimate total resource (*ResorTot*) by energy type from four parameters. Two parameters represent exogenous specification of conventional and

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[26] See Box 4.1 for equation notation; "Q" is often used by economists as the capital-to-output ratio.

unconventional resources, respectively (***resor*** and ***resoruncon***). The conventional/unconventional distinction has been common in energy analysis, and data sources still maintain it. For instance, we have looked to data from the BGR for estimates of unconventional energy resources. The other two parameters are exogenous multipliers on resource values (***resorm*** and ***resorunconm***).

$$ResorTot_{r,e} = \mathbf{resor}_{r,e} * \boldsymbol{resorm}_{\boldsymbol{r,e}} + \mathbf{resoruncon}_{r,e} * \boldsymbol{resorunconm}_{\boldsymbol{r,e}}$$

Earlier versions of IFs made a distinction between the capital costs of conventional and unconventional fossil resources (such as shale-bearing oil and gas). The advent of techniques such as fracking to extract unconventional resources, with cost structures that are not that different from the extraction of conventional ones in difficult environments (including the deep ocean), made such a binary cost structure much less meaningful. The current version of the IFs energy model, therefore, has moved to aggregate the two types of resources and to build a continuous structure of their increasing costs with resource exhaustion.

Resource constraints. In our database we do not make the same conventional and unconventional distinction for coal, nuclear, hydroelectric, and new renewable energy types as we do for oil and gas. The values of ***resoruncon*** for those are zero, and it is only the values of ***resor*** that matter. Also, the interpretation of resource constraints for nuclear, hydroelectric, and new renewable energy types is different from that for fossil fuels and is discussed next (before returning to fossil fuels).

For *nuclear energy*, we posit no resource constraints, and therefore no rise in capital requirements (*QE*) with exhaustion of any resource base (except exogenously with ***qem*** in scenarios). Fuel reprocessing and breeder reactors (and ultimately fusion systems) would support this inattention to resource limits and rising costs.

$$QE_{r,e,t+1} = BQE_{r,e,t} * \boldsymbol{qem}_{\boldsymbol{r,e}}$$

Hydroelectricity and other renewables have resource constraints on production.[27] Those constraints are related to appropriate siting. For renewable energy forms, the values specified for ***resor***, and therefore total resources (*ResorTot*), are ultimate annual production limits, not depletable stocks. The remaining resource (*ResorRem*) is conceptualized as the difference between the total resource available and the degree to which the current level of production (*ENP*) has grown from its value in the initial year (*ENPGrowth*). However, as the remaining appropriate siting approaches zero, the values of *QE* and *ENP* could become somewhat unstable. To avoid that, the computation of production growth uses a moving average or smoothed value of ENP (*SmoothENP)*.

$$QE_{r,e,t+1} = BQE_{r,e,t} * \frac{ResorTot_{r,e}}{ResorRem_{r,e}} * \boldsymbol{qem}_{\boldsymbol{r,e}}$$

where

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[27] Rogner et al. (2012, p. 431) state that renewable resource potentials "exceed even the highest future demand speculations by orders of magnitude." However, in century-long forecasting, there can be limits.

$$ResorRem_{r,e} = ResorTot_{r,e} - ENPGrowth_{r,e}$$

$$ENPGrowth_{r,e} = SmoothENP_{r,e} - ENP_{r,e,t=1}$$

$$SmoothENP_{r,e,t} = 0.8*SmoothENP_{r,e,t-1} + 0.2*ENP_{r,e}$$

In the case of *oil, gas, and coal*, total resources (*ResorTot*) are exhaustible rather than fixed (renewable). Cumulative production (*CUMPR*) is the sum across time of annual production (*ENP*); as it approaches the magnitude of total resources, the remaining resource category declines and drives up the capital-to-output ratio. The logic around remaining reserves (described earlier) prevents abrupt exhaustion and collapse of production, while the use of a limit on the run down of remaining resources (via the *MaxFac* variable set at 10% of total resources) keeps the capital-to-output ratio from going to infinity and shutting off fossil production well before resources are exhausted.

$$ResorRem_{r,e} = AMAX(ResorTot_{r,e} - CUMPR_{r,e}, MaxFac_{r,e})$$

$$CUMPR_{r,e,t} = CUMPR_{r,e,t-1} + ENP_{r,e}$$

$$MaxFac_{r,e} = 0.1*ResorTot_{r,e}$$

Further, to smooth model behavior for fossil fuels, particularly as resources begin to be exhausted, the capital-to-output ratio is calculated as a moving average.

$$QE_{r,e,t} = 0.8*QE_{r,e,t-1} + 0.2*CompQE_{r,e}$$

$$CompQE_{r,e} = BQE_{r,e}*\left(\frac{ResorTot_{r,e}}{resor\_rem_{r,e}}\right)^{0.4}*\boldsymbol{qem_{r,e}}$$

7.2.4.2 Other Important Energy Functions: Demand and Equilibration

Demand. As discussed earlier, many energy-forecasting models—especially shorter-term ones—distinguish different sectors of demand, such as transportation, residential, commercial, and industrial. Some also distinguish among primary energy (e.g., oil) and secondary or even tertiary forms (e.g., refined products or electricity). Fig. 7.9 showed, however, that there is a rather monotonically and understandably changing relationship between economic growth and energy consumption, much more so than we saw in the sources of supply (Figs. 7.7 and 7.8). That relatively greater predictability of demand led the IFs project to focus most model elaboration on supply.

Still, demand clearly needs serious attention also. The core of its representation in IFs involves change over time in the initial country-specific ratio of energy demand per unit of GDP in response to two factors:

- An exogenously specified rate of advance in energy efficiency per unit of GDP. This factor helped tune the model to historical patterns of energy demand (thus GDP and the energy intensity of it are the distal drivers of demand).

- A moving average of energy prices, which also incorporates exogenously specified carbon taxes, ***carbtax*** (the more proximate drivers).

There is very large initial disparity across countries in the ratio of energy demand to GDP. At something near the extreme, the Ukraine is about 10 times as energy intense as Italy. Such disparities are unlikely to persist over the longer term, and IFs represents a very long-term convergence of the ratios to a cross-sectionally estimated function against GDP per capita at PPP; that process will bring the energy intensity of the Ukraine, still reflecting subsidized energy prices in the communist era, down toward values like those of Brazil. The factors of prices and energy efficiency gains discussed earlier work on top of this convergence process.

Prices. The shorter-term equilibration of supply and demand in the energy model parallels that of the economic and agriculture models. Signals from levels of inventory stocks relative to desired levels, and from the rates of change in that discrepancy, adjust prices via the *ADJSTR* function of IFs (the PID controller, see Section 6.1.4.1). The model computes both country-specific prices and a global one, none of which are differentiated by energy type. Global prices are represented both in terms of a price index (base year = 100) and a dollar price per barrel of oil equivalent. Behaviorally, demand begins to respond more quickly to prices, but long-term supply elasticity (feeding through the logic of investment patterns) has a larger effect.

Investment and capital formation. Equilibration also involves investment and change in the energy capital stock (*KEn*). Investment is the primary factor in clearing the energy market in the longer term. The treatment of investment in energy in IFs is somewhat more complex than that of its treatment in agriculture. In energy, the process first involves calculating an estimate of total energy investment need (*TINeed*); then computing a separate demand or need for each energy type based on profit levels specific to each energy type; and, last, adjusting the total estimate based on the sum of the demands from each energy type.

The initial aggregate calculation of total investment need is a function of energy demand, adjusted by a number of factors, some of which are global and some country-specific:

- a moving average of the ratio of investment need to energy demand in a country (the product of this and energy demand provides a basic estimate of investment need each year)
- the ratio of global energy demand per unit of GDP in the current year to that in the previous year
- the ratio of global energy capital per unit of global energy production in the current year to that in the previous year
- energy stocks relative to target levels (a multiplier on investment need is responsive to the gap between stocks and their target level, as well as to the year-to-year change in that gap using the *ADJSTR* function [the PID controller] of IFs)
- the expected level of profits in the energy sector of a country, calculated as the ratio of returns to costs

Before this calculation of total investment need is passed to the economic model, it is checked against a bottom-up calculation of the investment needs for each energy type individually. Calculation of the investment demand by energy type also has several elements:

- profits for each energy type
- if the model user has set an exogenous target for production growth in an energy type, investment needs are based on proportional growth in the energy capital of that type

- reserve constraints specific to each country and energy type
- in any year the investment demand for each type of energy is not allowed to fall by more than 20% or increase by more than 40%

If the bottom-up demands are less than the top-down calculation, the latter is brought down halfway to the former, and such constriction of investment will ultimately raise prices and the returns needed to make specific energy types profitable. In the economic model, the desired total investment in energy (TINeed) must compete with other sectors for investment. Once sectoral investments are determined, a final value for energy sector investment is passed back to the energy model, and specific investment by energy type is adjusted proportionately to demand. Investment augments capital stocks, and depreciation (governed by a capital lifetime) decrements them.

More generally with respect to energy and economic model linkages, the energy model provides trade, converted to currency, to the economic model. It also provides energy demand.

7.2.4.3 *Limitations*

Although most energy models distinguish among final energy demand categories (e.g., manufacturing versus residential), IFs does not. Nor does it build in intermediate or processed energy forms, notably electricity and gasoline, and potentially hydrogen. Models that elaborate the supply-through-demand flow pattern have advantages, including detailed accounting of losses in conversion processes. One potentially important offsetting disadvantage of these models, however, is that such elaboration of energy flows can introduce rigidity in the process of substitution across primary sources. Consider the current movement of transportation systems from liquid fuels to electricity supplied by a wide range of sources, including new renewables. Because that transformation is in early stages, the details of energy engineering around it are highly uncertain, and any specification of them could lead to locking in existing technological structures and underestimating the speed of substitution of new renewables for fossil fuels. Thus there is an argument for a simpler system that facilitates very rapid substitution as technologies and costs change.

A limitation on the primary energy side is that IFs does not represent traditional biomatter use except in the health model's treatment of cooking with traditional fuels. Nor does it break down new renewables into wind, solar, and geothermal (or even more elaborate subcategories).

One of the most difficult variables to represent, but fundamentally important in supply-side energy analysis, is the future cost of various energy forms, including the new renewables. The use in IFs of exogenously specified technological progress is functional, but perhaps not as strong an approach for near-term forecasting as explicit mapping of cumulative future production of each source against cost structures would be. Such a mapping shows the typically rising costs of fossil fuels (subject to downward shifts with technological advance) and the typically falling costs of new renewables (based on both technological advance and economies of scale). On the other hand, technological change can rapidly alter not just the overall level of cost structures against different supply sources, but also the shape of them, as it has with oil and gas in shale. Hence, again, such elaboration could introduce inappropriate rigidity.

7.2.5 Comparative Scenarios

A special section of the January 2017 issue of *Global Environmental Change* focused on quantification across the dimensions of the shared socioeconomic pathway narratives. One paper (Bauer et al., 2017) presented quantifications by six IAMs of energy projections for the five SSP scenarios. While a single IAM produced the official marker scenario for each SSP (MESSAGE with GLOBIOM was used to produce it for SSP2), all six of the IAMs represented SSP2 as well as one or more of the other SSP scenarios. The other IAMs were AIM/CGE, GCAM, IMAGE, REMIND with MAgPIE, and WITCH with GLOBIOM (see Section 3.2 for basic information about each of these IAMs). If there is one primary take-away from the analysis, it would probably be the great uncertainty around global energy futures. For example, total energy sector growth varies from 40% to 230% across the scenarios and models (Bauer et al., 2017, Abstract).

Focusing on SSP2 (the Middle of the Road scenario) across the IAMs listed previously, however, Fig. 7.10 shows fairly similar primary energy production projections across the century, with the total rising from about 500 exajoules (EJ) in 2010 to about 1000–1200 in 2100. The spread of near-century-long energy growth across the six models of the Bauer et al. study for SSP2 is only from 141% to 181%, reflecting relatively low uncertainty around energy demand in the Middle of the Road scenario. However, the rise is higher in the IFs Base Case (which is fairly close to SSP2 projections in most issue areas), to 1372 EJ, a result related in part to the differences in assumptions between the other IAMs and IFs with respect to the future costs and availability of renewable energy forms. In IFs, lower costs of renewables help drive both higher overall demand and a different supply mix.

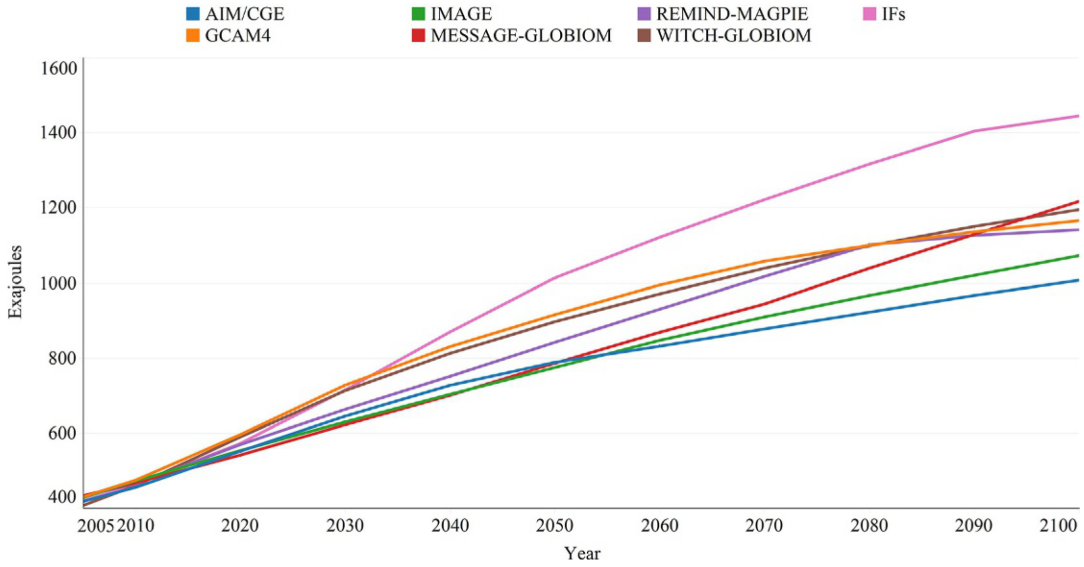

FIG. 7.10 Global primary energy production: Comparative SSP2 scenarios to 2100.
Note: The six IAMs other than IFs produced the official SSP energy projections (see Bauer et al., 2017).
Source: IFs Version 7.36, initialized with data from International Energy Agency; comparative SSP2 scenarios from SSP database (Version 1.1) hosted by IIASA at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

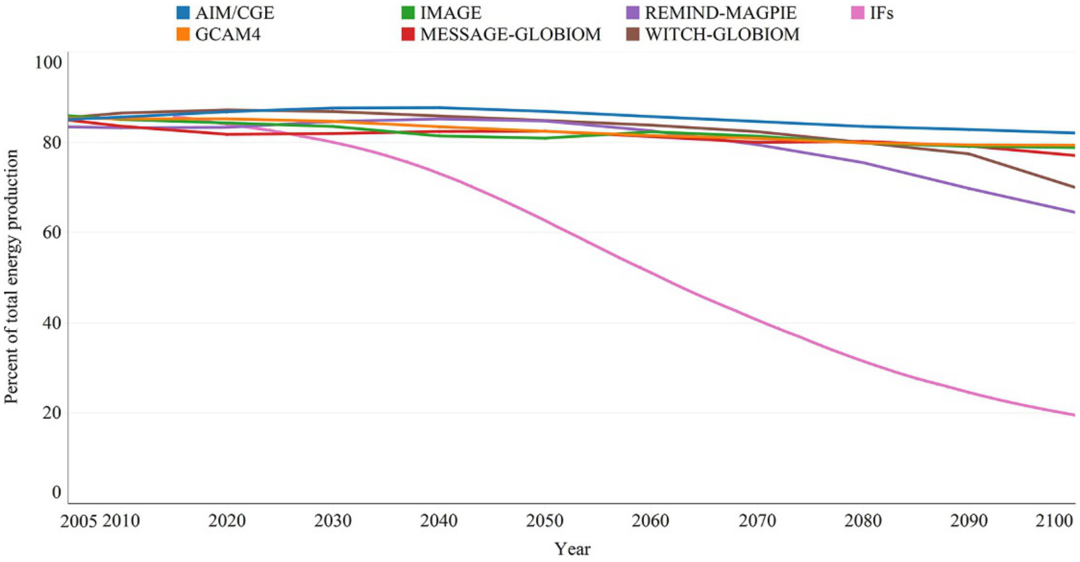

FIG. 7.11 **Fossil energy production: Comparative SSP2 scenarios to 2100.**
Note: *The six IAMs other than IFs produced the official SSP energy projections (see Bauer et al., 2017). IFs values do not include biomass and represent hydropower using the substitution method (amount of fossil fuel replaced for equivalent electricity output). Source: IFs Version 7.36, initialized with data from International Energy Agency; comparative SSP2 scenarios from SSP database (Version 1.1) hosted by IIASA at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.*

Fig. 7.11 shows that difference in energy mix very starkly by focusing on the fossil fuel (coal, oil, and gas) share of the energy supply, a share that obviously has very important implications for carbon emissions and warming (picked up later in this chapter). In IFs, the fossil fuel share declines by 6% even just between 2015 and 2030, and the decline continues to accelerate, not because of fossil resource shortages, but because of the growing attractiveness of renewable forms (buttressed by already existing policy support for them). The share of energy from non-fossil sources in the IFs Base Case scenario climbs to 31% already in 2050 and nearly 80% in 2100. MESSAGE suggests a non-fossil level of 17% in 2010, climbing to only 23% in 2100 for the official marker version of SSP2.[28]

Why the dramatic differences between the values coming from IFs and those coming from MESSAGE and other models replicating SSP2? O'Neill et al. (2017, p. 173) identified SSP2 as the "middle of the road" scenario, in which:

> The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns…. Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources.

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[28] In a different study within the same issue of *Global Environmental Change*, TIMER represents a non-fossil contribution to primary supply in 2010 of 20–25% (including biomass, which IFs does not include) and in SSP2 that climbs to about 30% in 2100 (van Vuuren et al., 2017, pp. 242–243 [using text and Figure 3]).

In fact, however, the growth of new renewables relative to fossil sources has been very rapid in recent years, driven by a technological trend that has decreased their costs dramatically in a short time. For example, one recent finding of the ADVANCE model intercomparison project (Luderer et al., 2016, p. 10) is that

> Most previous modeling studies have underestimated the role of wind and solar because of overly conservative assumptions on technology costs and the challenges related to coping with a variable renewable electricity supply.

Although shares of new renewables in the total energy mix remain extremely low, their production growth rates have been dramatic. Many sociopolitical units are targeting major growth in their contribution to electricity production (to shares of 20%, 30%, or much more well before 2050), even as electricity's contribution to total final demand is growing in part because the transportation sector is beginning to significantly increase use of electricity (plug-in vehicle sales reached 1.2 million in 2017 in continuation of a sharp rise).[29] The IEA *World Energy Outlook 2016* reported that additions to electric generation from renewables between 2012 and 2020 would exceed additions from all other sources combined (IEA, 2016, p. 82). In my view, the operationalizations of SSP2 have been very conservative with respect to building on the policy- and technology-driven growth of new renewables over the last decade. If total global primary energy demand grows by a factor of about 2.5 between 2010 and the end of the century, I find it difficult to conceptualize a world in which new renewable production grows by less than twice that (thereby doubling its share).

The IFs Base Case value for non-fossil sources in 2100 might be considered an outrageously high value from a simpler energy model than those of other IAMs, but it is not alone in defining such a path. The *World Energy Outlook 2017* (IEA, 2017, p. 79) elaborated three scenarios. In New Policies, its equivalent of a base case that builds in recent actions and intentions, the fossil fuel share of primary energy drops by six percentage points between 2016 and 2040; in its prescriptive Sustainable Development scenario it falls by 20 percentage points.[30] The decline in the IFs Base Case scenario is 13 percentage points.

This contrast of the Base Case forecast of IFs with the SSP2 scenarios of major IAMs begins to suggest the uncertainty that we face this century with respect to energy supply futures. One can also see that uncertainty to some degree across the energy projections for the full range of SSPs in the IIASA SSP database. SSP1 is the most environmentally friendly, while SSP3 tends to be the least friendly. The non-fossil contributions in SSP1 by 2100 are much higher than in SSP2 (approximately 50 percentage points higher in the IMAGE/TIMER version of it).[31]

The IAM community has developed other—more heavily policy-driven—scenarios over time, in which non-fossil sources could provide nearly 50% of energy supplies even by 2050. Using TIMER, van Vuuren and Kok (2012, p. 34) identified three scenarios (Global Technology pathway, Decentralized Solutions pathway, and Consumption Change pathway) that produce between 38 and 48% non-fossil energy in 2050 (compared

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[29] See www.ev-volumes.com.

[30] The Energy Transitions Commission (2017, p. 40), bringing together leaders of major energy companies and other energy experts, suggested that clean electrification could replace 10–20% of fossil fuel use by 2040.

[31] Based on projections at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

with 35% in the IFs Base Case), with an average of an additional 20% of supply from fossil fuels using carbon capture and sequestration. Similarly, using MESSAGE, the Global Energy Assessment summary report (GEA, 2012b, p. 9) and its larger full report (GEA, 2012a, Chapter 17) elaborated three sets of scenarios (GEA-Efficiency, GEA-Mix, and GEA-Supply), all of which suggest possible energy futures by 2050 in which fossil fuels contribute less than 50% of primary supply.

Uncertainty about global energy futures is obviously very great, more so than we have seen around other issues in this book, including population, education attainment, and economic growth. Such uncertainty will, of course, greatly affect projections of future carbon emissions and global warming, to be discussed later in this chapter.

7.3 INFRASTRUCTURE[32]

Based on data from many sources, IFs calculates that in 2015 more than 1.2 billion people had no access to electricity. About 700 million had no access to safe water from any source, and another 2.5 billion did not have water pipes to their homes. Approximately 1.7 billion had no access to improved sanitation, and another 600 million had only shared access with other families. More than 2.4 billion people still cooked with solid fuels, such as wood. Twenty-seven percent (or 700 million) of the world's rural population of 3.4 million did not live within two kilometers of an all-season road.

The good news is the ongoing decrease in the percentages (and even total numbers) of people deprived of basic life support systems now taken for granted in the high-income world—even if progress is slower than we want. For instance, those globally without safe water declined from 25% in 1990 to 10% in 2015, as those without any form of improved sanitation fell from 44 to 24% during the same period. Also good news is that globally there were approximately 100 mobile phone subscriptions for each 100 persons (60 per 100 even in Central Africa), although many people have more than one mobile device, so that about 40% globally are without any. This spread of mobile phone subscriptions demonstrates the rapid take-up of infrastructure by even the poorest when it becomes feasible.

7.3.1 Concepts, Structures, and Data

As in other issue areas, it is useful to think about stocks and flows when conceptualizing infrastructure. The extent of access to infrastructure has special importance in the modeling and analysis of infrastructure. That access is a stock directly related to the accumulated capital stock underlying the infrastructure; access rises with new investment flows and extension of service, and it can fall if systems are not built and maintained.

Indicators of physical extent and access rates include kilometers of road and access by rural populations to all-season roads, electricity generation levels and urban and rural access rates, portions of populations connected to improved sanitation and piped water or having improved cook stoves, extent of wastewater collection and treatment, and portions of

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[32] Dale S. Rothman led the effort to develop the IFs infrastructure model and Mohammod T. Irfan was critical in its implementation. See Rothman and Irfan, 2013 for documentation.

population with connection to telephone lines, mobile phones, and broadband services. For both water and sanitation, there are ladders of access, generally including no improved access (use of untreated surface water sources and open defecation), through shared access to various forms of improved facilities, to improved on-premise water and sewage removal.[33]

With respect to uncertainties, the greatest are the extent of investment in infrastructure and the impact that has on access levels—although the pattern of advance in technology is also a significant determinant of access and another source of uncertainty. Much infrastructure, including both roads and core networks of systems like water, sanitation, electricity, and communications, has the character of a collective good that benefits heavily from public spending and facilitation (including that of public-private partnerships) as well as the character of a networked system that is open to all with relatively low marginal cost. Spending on public or collective goods is generally subject to uncertainty and underprovision (Olson, 1965), even while expansion of networks tends to benefit from the extent of earlier build-out.

With respect to forward linkages from infrastructure access, important ones include health and wellbeing, education, economic productivity, and environmental impact (to which the next sections of this chapter turn).

A major problem for infrastructure modeling is that data are very difficult to obtain even on the extent of infrastructure and access to it, much less on capital stock in financial terms. In part, that is because there is no central source for such information. Major intergovernmental organizations have missions related directly to almost all of the other issue areas discussed in this volume: population (the United Nations Population Division), education (United Nations Educational, Scientific and Cultural Organization); health (World Health Organization), economics (Organisation for Economic Co-operation and Development, along with the International Monetary Fund and World Bank), food and agriculture (Food and Agriculture Organization of the United Nations), and energy (International Energy Agency). Those organizations collect information, often make projections, and/or support efforts to improve conditions in countries around the world related to their respective issue area. No such central source exists with respect to infrastructure. While there are organizations focused on one or another specific infrastructure type (e.g., the International Road Federation, or the International Telecommunications Union), there is no integrated body focused on infrastructure as a whole.[34] This complicates any effort to build a forecasting capability for global infrastructure, as does the desirability of differentiating public and private spending, for which data are also extremely scarce to nonexistent. The IFs project needed to extract information from many disparate sources and develop as systematic a schema as possible for the various estimates and their change over time. See Rothman et al., 2014, including Appendix 4A, for explanation on this issue.

7.3.2 Infrastructure Transitions

Although historical global data series on infrastructure are not strong, especially before 1990, some patterns can be seen in the data that are available. For instance, even while miles

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[33] The WHO/UNICEF Joint Monitoring Programme revised its water and sanitation ladders in 2017; see https://washdata.org/monitoring/drinking-water.

[34] A Global Infrastructure Facility (GIF) was established in 2015 under the leadership of the World Bank, with broad public and private partner participation. The GIF is focused on facilitating and supporting complex infrastructure projects that are beyond the scope of any single institution, but not on data. See www.globalinfrafacility.org/.

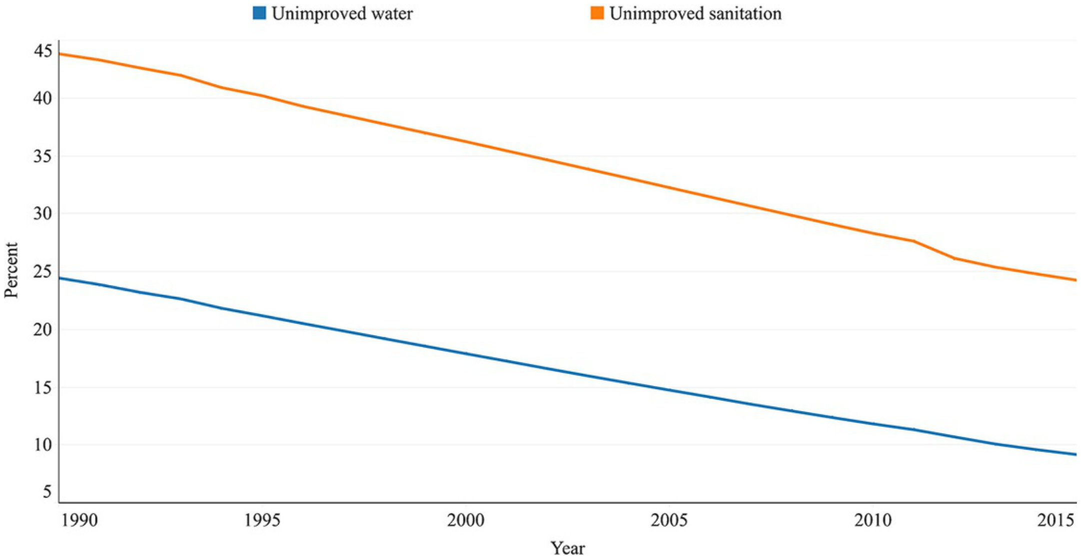

FIG. 7.12 **Percent of world population with access only to unimproved water and sanitation from 1990 to 2015.** *Source: IFs Version 7.36, using data from the WHO/UNICEF Joint Monitoring Programme.*

of global road have increased pretty much in lock step with global population since the early 1960s, the share of them that are paved rose from 47 to 60% between 1990 and 2011 (World Development Indicators data from multiple sources).

Fig. 7.12 shows the rapid global reduction in recent years with respect to the portions of population without even shared access to improved water sources and improved sanitation. Clearly, the rates of improvement have been quite dramatic, reducing the portion without safe water by well more than half between 1990 and 2015, the period over which the original Millennium Development Goals called for such advance. Although the MDG goal of reduction by half in the percentage of persons without access to improved sanitation was not reached by 2015, the percentage points of decline for those without access to improved sanitation exceeded the percentage points of decline for those without an improved water source.

Turning to electricity, Fig. 7.13 shows the rates of access for populations in the United Nations subregions in 2013 as a function of GDP per capita at PPP. The figure indicates not only the effective attainment of universal access in high-income regions, but also in East Asia and South America at much lower income levels. Further, it suggests the successful push that most of the world has made toward that goal with all but three subregions in Africa at or more than 80% access. The low electricity access levels in those African subregions correspond to their low levels of development more generally, including low rates of urbanization and deficiencies in governance. With respect to the future, it is hard not to expect a continuing big push for universal electricity access even there, given the sharp rise in access rates as GDP per capita rises and technology advances. As indicated earlier, the speed of ICT uptake clearly indicates the desire for infrastructure. Already by 2015, mobile phone subscriptions per hundred persons had reached 59, 59, and 90 in Eastern, Middle, and Western Africa, respectively (data from the International Telecommunications Union).

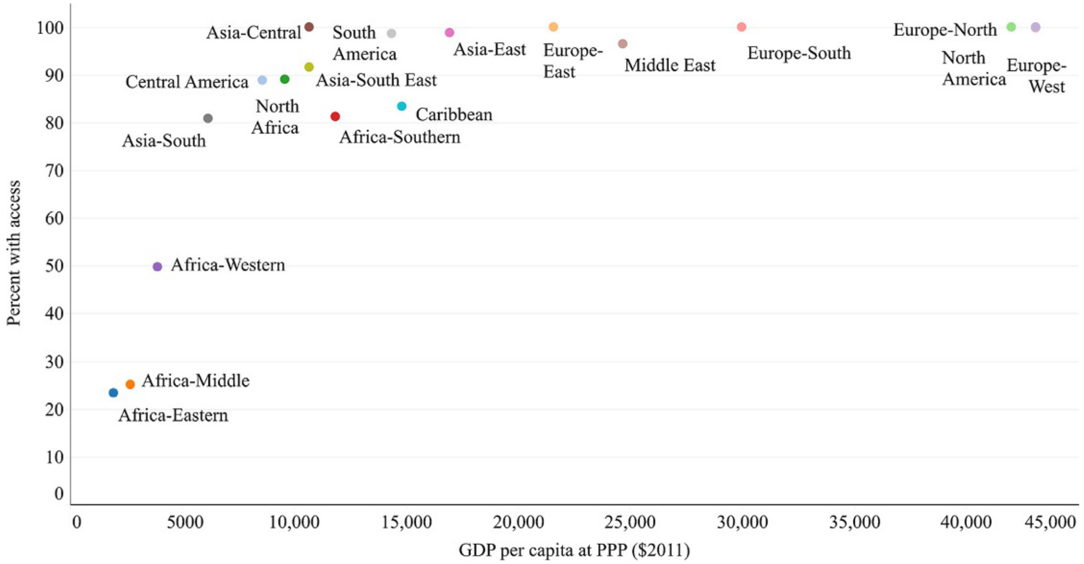

FIG. 7.13 **Relationship between GDP per capita and access to electricity in 2014.**
Note: *Uses United Nations subregions and includes both urban and rural populations.*
Source: IFs Version 7.36, using data from the World Bank's World Development Indicators.

7.3.3 Modeling Infrastructure

Modeling efforts are rarer with respect to infrastructure than with most of the other developmental components included in IFs. Rothman et al. (2014, pp. 14–15) included a review of efforts, noting that foundational studies often originated in the World Bank. Among those are the work of Fay (2001) and Fay and Yepes (2003) who developed methods to estimate needs for investment in transportation, power, water and sanitation, and telecommunications infrastructure. While early studies had short horizons, generally only five to 10 years, later ones—such as G. Hughes et al. (2010), Kohli and Basil (2011), Kohli and Mukherjee (2011), and Stevens et al. (2006)—extended the horizon as far as mid-century. In many respects, the work closest to that of the IFs project might be that of G. Hughes et al. (2010), which extended the time horizon to 2050 in order to explore the global infrastructure costs of adapting to climate change.

In association with its work on the World Energy Model, the IEA developed a foresight capability for electricity access (IEA, 2015, pp. 48–49). The IEA set a threshold for access as not simply a supply connection, but instead having at least 250 kW-hours per year for rural households (enough for "a floor fan, a mobile telephone and two compact fluorescent light bulbs for about five hours per day") and double that for urban ones. In terms of drivers, the IEA includes distal variables such as per capita income, urbanization (facilitating network connections), and technological advance, as well as more proximate ones such as fuel prices, subsidies, and energy access programs. The IEA also projects reliance on traditional use of biomass for cooking versus modern fuels with a similar set of drivers.

Despite the advances made in infrastructure modeling, most studies are quite narrowly focused by geography, infrastructure area, or temporal focus, and they tend not to look at both financial needs and funding availability in order to consider how needs might be met, much less what trade-offs with other funding needs might be involved. Further, within the multi-issue world modeling and IAM traditions, there has been limited work on infrastructure. Exceptions include attention to electricity access (including off-grid sources) in the IMAGE suite in TIMER, to clean water and sanitation in GISMO, and to the ecological impact (e.g., species disturbance) of roads, power lines, and pipelines in GLOBIO.[35]

7.3.4 Infrastructure in IFs

As Rothman et al. (2014) emphasized, desire to increase levels of access has driven most infrastructure modeling. In the case of IFs, the specific infrastructure forms represented by access rates are rural road access (portion of population within two kilometers of an all-season road), electricity, safe water, improved sanitation, wastewater collection, fixed telephones, fixed broadband, mobile telephones, and mobile broadband (Rothman et al., 2014, p. 85). In addition, IFs represents physical amounts of the infrastructure forms underlying that access including, among others, paved and unpaved roads, electricity generation capacity, electricity connections, and area equipped for irrigation.

The model further represents financial costs of building and maintaining such infrastructure. Whereas in agriculture and energy most investment is private, in the case of infrastructure much spending is public (but least so with communications). Therefore, as discussed in Sections 6.1.4 and 6.2.4, the infrastructure model is connected to the government finance model and the social accounting matrix. Because IFs does not cover all infrastructure categories explicitly (omitting, for instance, rail systems, seaports, and airports), it needs to account for the residual spending on such infrastructure, and it uses an "other infrastructure" category to do so. Infrastructure spending for both explicitly represented and other infrastructure forms competes with spending for health, education, the military, R&D, and a residual category. Insofar as I know, the broad accounting in IFs for infrastructure finance is unique in global forecasting.

Because our literature analysis suggested strikingly limited variation of infrastructure costs per unit as a function of GDP per capita across country economic development levels (e.g., Fay and Yepes, 2003, p. 10), the IFs project used the same "best practice" unit costs for all regions of the world as the Base Case default (although, of course, such unit costs vary by infrastructure type). Parameters allow setting lower and upper cost values per unit of infrastructure with interpolation across a specified range of GDP per capita. Little variation of unit costs with GDP per capita could potentially reflect the capital intensity of much infrastructure development (as with capital-intensive energy investment, where capital per unit of production varies with resource quality rather than country income level).[36] Most developing countries have access rates far below the nearly saturated levels of high-income countries, and therefore are striving to rise simultaneously and rapidly up the access curves of many core

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[35] The United Nations Environment Programme (2001, p. 13) analyzed impacts associated with three different scenarios of infrastructure development, with a focus on the Arctic through 2050.

[36] Within our own modeling team, the representation of infrastructure cost structures across different economic development levels was a subject of considerable debate.

infrastructures. Using costs per unit similar to those of rich countries means that our projections of infrastructure spending by developing countries as a portion of GDP tend to be considerably higher than in more developed countries; simultaneously, absence of rise in unit costs with GDP per capita also generates projections of spending needs in high-income countries that decline over time relative to GDP. The model, however, does include multiplier parameters that allow changes in costs across time for each infrastructure type and country. It further includes a structure that allows the user to interpolate between lower and higher unit cost specifications with rise in GDP per capita.

Although there are important uncertainties around unit costs and finance availability, the discussion here focuses on the critical expected access formulations, which definitely change with development levels. It uses water and sanitation (watsan) as illustrations because of their centrality to global goals, importance to health, and ties to the environment.

7.3.4.1 Expected Access Rates

IFs uses a generalized nominal logistic approach to determine the share of the population that would be expected to have access to each type of infrastructure given selected independent variables. For both water and sanitation, the model represents three categories of access (with standard names that are not ideal).[37] For water, they are (1) no improved access, (2) other improved access (i.e., other than piped, including a shared well), and (3) piped; for sanitation, they are (1) other unimproved access (i.e., open defecation), (2) shared access (including latrines), and (3) improved access.

As with the Cobb-Douglas production function in economics and the mortality function from the Global Burden of Disease project in health, it is useful to show a generalized functional form for expected access. The values of p_i represent the share of population with access to each of these categories; the values will all fall between zero and one and will sum to one. Multiplied by 100, these provide population access percentages in each category.

$$p_i = \frac{s_i}{1 + \sum_{i=1}^{2} s_i} \text{ for } i = 1 \text{ to } 2.$$

and

$$p_3 = 1 - \sum_{i=1}^{2} p_i$$

and

$$s_i = e^{\left(a_i + \sum_{j=1}^{n} b_{i,j*} x_j\right)} \text{ for } i = 1 \text{ to } 2.$$

where n is the number of explanatory variables.

Our estimations for water and sanitation were unusual in identifying two longer-term or distal developmental variables—both GDP per capita at PPP (*GDPPCP*) and adult years of

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[37] When the project updates water and sanitation access categories in light of the WHO/UNICEF Joint Monitoring Programme's 2012 revised definitions, with their division of improved access into five subcategories, the category names in IFs will change and, unless some of the new categories are combined, the number of categories may change.

education (*EDYRSAG25*)—rather than only one or the other (their close correlation typically causes one to drop out). The analysis also found the portion of population in extreme poverty to be important (*INCOMELT125CS2005*), thereby bringing in a variable that reflects inequality. Finally, the portion of GDP spent by government on health (*GovtHl%GDP*), most clearly capturing a more immediate policy orientation, proved useful. As with model variables in other issue areas, the calculations of the above equations are subject to a variety of adjustments to fit initial data (shift factors) and to introduce scenarios (both multiplier and future target specifications).

Not surprisingly, the portion of population with access to wastewater collection varies statistically with the portion that has improved sanitation. It also rises with the portion of the population that is urban. The portion of population served by treatment of that wastewater rises with the rate of its collection and with GDP per capita at PPP.

Functional forms with an inverted exponential form (which produces saturating behavior) were also used for projecting access to paved roads, to electricity, and to modern fuel replacements of solid fuels in cooking. Most of the other formulations for access variables drew upon logarithmic or second-order polynomial forms because of a similar need to represent saturating behavior as rates approach 100% (Rothman et al., 2014, pp. 94–98).

Public financing demand is the sum of expenditures to build new infrastructure for expanding access to "expected" (or in scenarios, "desired") levels and of expenditures for maintenance of existing infrastructure. The government finance model determines what can be allocated, and that sum is distributed proportionately to the demands of individual infrastructure forms. It is assumed that for each infrastructure type private financing is available in (differing) constant ratios with public financing; private financing funds a much higher share of ICT than other infrastructure forms.

7.3.4.2 Other Important Functions

Carrying forward information from infrastructure access to multifactor productivity (MFP) and to economic growth benefits from aggregation of the large number of access rates across infrastructure forms. Following the approach of Calderón and Servén (2010), IFs uses a traditional infrastructure index with all of the forms that IFs explicitly treats (other than ICT) scaled, standardized, and weighted equally.

It is not desirable to follow the same approach for ICT because of the extremely rapid growth of those technologies in recent years and in expectations across all levels of income for the near-term future. Instead, we focus on the S-shaped pace of advance in access (rather than the extent of it) for change in a separate ICT index (see also Qiang et al., 2009).

Section 6.1.4 touched on the manner in which the two infrastructure indices enter into the physical capital element of MFP. The scaling of impact also looked to the literature that helped us develop the indices. In addition, we fed forward aspects of infrastructure to health using the proximate variable approach that Section 5.2.4 discussed. Specifically, we looked to the impact of unsafe water and sanitation on diarrheal disease, which in turn affects undernutrition as well as mortality, and the impact of cooking with solid fuels on indoor air pollution and thereby on respiratory diseases, such as chronic obstructive pulmonary disease (see also Hughes et al., 2011, pp. 95–100).

7.3.4.3 Limitations

One significant limitation in the current IFs infrastructure model is its failure to treat infrastructure types more comprehensively. Railroads, ports, and airports are among obvious omissions. The data and modeling demands for each infrastructure form are intensive, and it seems unlikely that IFs will ever have a fully inclusive infrastructure model. The "other infrastructure" category of IFs in its governance finance representation provides a proxy that allows comprehensive coverage there. A failure to link spending on that other infrastructure to MFP and economic growth remains.

A second important limitation is the absence of forward linkages to environmental impacts, such as air pollution and biodiversity. Some positive forward linkages, such as help for students (especially girls) to reach schools and impacts on health from transport- or communication-based access to comprehensive health care, are also missing.

A third limitation, as discussed earlier and rooted partly in data scarcity, concerns the representation of changing infrastructure costs across countries and time only via scenario specification. And a fourth limitation, linked to conceptualization and data, is that the model structure does not yet represent the revised water and sanitation ladder categories established by the WHO/UNICEF Joint Monitoring Programme in 2017.

7.3.5 Comparative Scenarios

There are a small number of long-term global infrastructure scenarios with which we can compare our own. With respect to electricity access, the New Policies scenario of the IEA's *World Energy Outlook 2016* (the central scenario between the Current Policies and the 450 scenarios)[38] anticipates that the number of people globally without access to electricity will decline from 1.2 billion in 2015 to around 780 million in 2030 and 540 million in 2040.[39] In the IFs Base Case (with attention to basic connection rather than to usage levels above a threshold as in the IEA projections), the decline in those without access is slower, from one billion in 2015 to 832 million in 2030 and then 750 million in 2040. The IEA projects that those without access to modern fuel-based cooking will drop by one-third from 2.7 billion in 2015 to 1.8 billion in 2040. In IFs, the respective numbers are a very comparable 2.4 and 1.5 billion. Both sources compute values down to the country level.

Additional infrastructure access projections come from the IMAGE model suite. It projects that the number of people without access to safe drinking water or improved sanitation will decline from about 2.6 billion in 2010 to about 1.4 billion in 2050 (Stehfest et al., 2014, p. 49; originally van Vuuren and Kok, 2012, p. 95). The IFs Base Case more optimistically anticipates that those without access to improved sanitation will decline from about 2.5 billion in 2010 to 950 million in 2050. IFs estimates those without safe water (most of whom are also without access to improved sanitation) will drop from 817 to 333 million over the same period. Given that the technology is well understood and relatively affordable, the key issue is political will

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[38] The 450 scenario refers to keeping the atmospheric carbon dioxide level at or below 450 ppm in an effort to hold global temperature rise to 1.5 °C.

[39] See http://www.worldenergyoutlook.org/resources/energydevelopment/ and http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessprojections/.

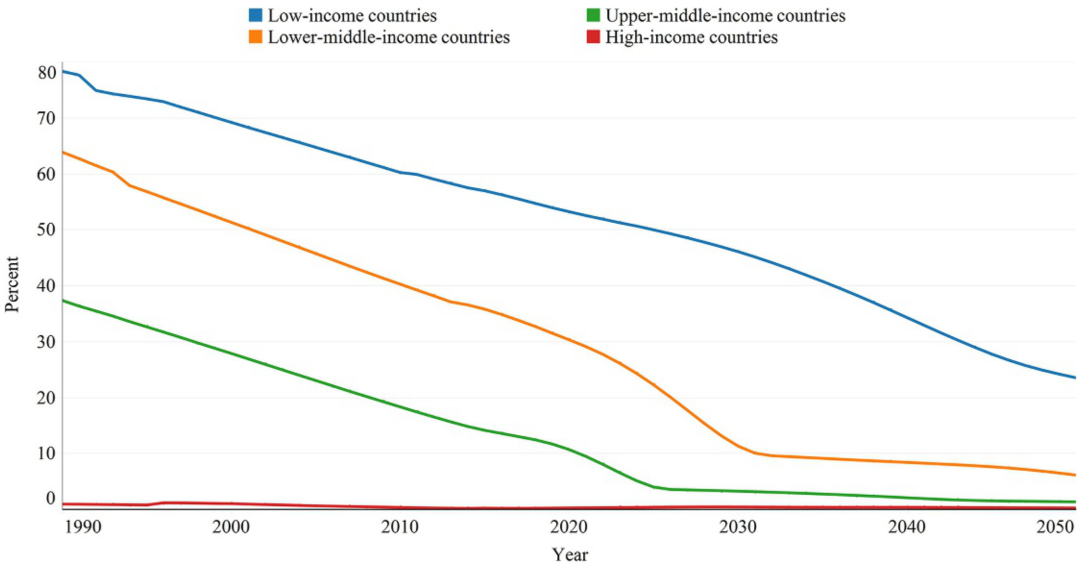

FIG. 7.14 **Population (percent) without access to improved sanitation by country economy classification: History and IFs Base Case scenario to 2050.**

Note: Uses World Bank classifications based on gross national income per capita. Includes those without either private or shared improved facilities.

Source: IFs Version 7.36, using historical data from the WHO/UNICEF Joint Monitoring Programme.

and investment. Our lower numbers represent in part the momentum for improvement that has continued to build with the MDGs and SDGs.

It is also potentially useful to compare the IFs Base Case with the global targets of the MDGs and SDGs, including universal access to safe water and to improved sanitation. While only about 60% of people have piped water, fewer than 10% now lack some source of safe water. With respect to improved sanitation, however, those with no access still account for nearly one-fourth of the global population. Fig. 7.14 shows historical data and the IFs Base Case for the decline in the rates of those without any access to improved sanitation by country income category, suggesting that the target of universal access to improved sanitation by 2030 is all but impossible to meet.

7.4 HUMAN IMPACTS ON BIOPHYSICAL SYSTEMS: AN INTRODUCTORY NOTE

It is worth a look back at Fig. 3.1, which shows the many human and natural systems of interest to integrated assessment modeling. This volume has devoted a great deal of attention to the human systems, ranging across almost all of those identified there. Earlier chapters treated population, health, education, the economy and governance. In this chapter, we have discussed agriculture/food, energy, and infrastructure as human systems that interact especially closely with natural ones. IAMs focus greatest attention on the first two of these, especially on the impacts of energy and agriculture on carbon emissions, the carbon cycle, and global warming.

Conceptually, human activities negatively affect the environment in three primary ways: (1) extraction/use, (2) emission/release, and (3) other disruptions (such as causing species extinction). For example, agriculture (1) extracts nutrients from the soil, often degrading it, and extracts water from natural systems to support agricultural use, (2) releases chemicals from pesticides and fertilizer into soil, water, and air, and (3) disrupts natural vegetation patterns as well as patterns of movement and even ultimate viability of many plant and animal species. Energy systems have similar impacts, including extraction of fossil fuels (and the ongoing destruction of forests for wood burning in some countries) and emissions into the atmosphere of carbon dioxide and other chemicals associated with the burning of fossil fuels. Infrastructure's most obvious impact is disruption of ecosystems (including migration and breeding patterns) and the facilitation of the environmental impact of all human economic activities, including food and energy production and use.

IFs, with its heavy emphasis on human and social development, does not have as complete a representation of natural system impacts as do many IAMs, in particular omitting, as of this writing, attention to greenhouse gases other than carbon. Yet, the three human systems that this chapter has considered have a number of important linkages in IFs to natural systems:

- *Agriculture*. IFs represents changing land use (e.g., forest conversion to crop or grazing area). Also, IFs represents the net carbon impact of deforestation. The IFs water submodel (discussed later in this chapter) addresses the demand that irrigation places on water supplies. However, IFs does not represent several other important environmental impacts of agriculture and food systems, including soil loss, methane emissions from cattle flatulence, and challenges to viability of species (including overfishing).
- *Energy*. Major impacts in IFs, noted earlier and discussed later, are both the progressive extraction of fossil fuel resources and the carbon dioxide (CO_2) emissions from fossil fuel use. IFs, however, does not directly address broader air and water pollution by energy systems, including that of the nuclear fuel cycle.
- *Infrastructure*. The treatment of infrastructure in IFs does not include direct environmental impact beyond the important health implications of urban air pollution and indoor solid fuel use. Land use for infrastructure has major effects on the environment that IFs does not address.

Some other human system impacts on biophysical systems are not included in IFs (and tend to receive limited attention in IAMs generally). For instance, while the economic model of IFs includes an "other primary" sector (other than agriculture and energy), the model does not physically represent that sector's activities, the most important of which environmentally is mining of a wide range of materials. Specifically, the largest human impacts by million tons of annual material extraction are iron (1350), aluminum (50), manganese (18), copper (16), chromium (16), zinc (14), lead (4), and nickel (2); Sverdrup and Ragnarsdóttir (2014, p. 211) have undertaken modeling of such minerals production and use.

Further, IFs and most other IAMs do not elaborate the multiple environmental impacts of urbanization, even as the global urban population share has come to exceed 50% and continues rapid growth (an exception is the work of O'Neill et al., 2010). Also, domestic and international security systems have significant and potentially tremendous implications for natural ones. The discussion during the Cold War of nuclear winter emphasized the potentially devastating consequences of nuclear war for the environment, but the lower level conflicts that are continually ongoing around the world always affect the environment. Although this impact of human systems on natural ones can be very significant, it does not appear in global models. The impacts of both urbanization and conflict may be omitted in part because of their local specificity.

The list of actual and possible linkages in global models from human activities to natural systems is lengthy. This chapter treats a restricted set, focusing on (1) greenhouse gas emissions with associated global warming and (2) demands on fresh water supplies.

7.5 CLIMATE CHANGE

More than any other issue, global warming and associated changes in precipitation patterns have motivated and defined integrated assessment modeling.

7.5.1 Concepts, Structures, and Data

Almost all IAMs represent greenhouse gas emissions, the carbon cycle, and global warming, especially from fossil fuel use. Several elements define the modeling steps of interest to us:

Step 1. Computing annual emissions. Although other greenhouse gases, notably methane and nitrous oxide, are very important, carbon dioxide from fossil fuel use and cement production receives the most attention.

Step 2. Specifying the full set of flows in the global greenhouse gas system and the associated stock levels, especially in the atmosphere (generally measured in terms of parts per million [ppm]).

Step 3. Representing the implications of those stock levels of greenhouse gases for changes in temperature and precipitation.

Step 4. Linking those changes forward to other biophysical system variables including sea level rise and plant growth, but potentially much more (including biodiversity). This step further changes emissions patterns and requires an iterative or recursive process linking back to *Step 1*.

For this volume, and in integrated assessment models including IFs, there is a fifth important but often underdeveloped step of interest to us:

Step 5. Feeding back biophysical changes broadly to social and human development, including to economic growth, social stability, poverty, and health. Again, this inherently should be a process that interacts iteratively with earlier steps. The generally fairly simple cost–benefit models of climate change that Section 3.2.2 discussed have taken this fifth step only to a limited degree, and the larger IAMs have often done even less of it, focusing heavily only on agriculture and energy, which are at the bridge between biophysical systems and human wellbeing. The next chapter focuses on this critical step.

While the greenhouse gas stock level of *Step 2* is critical with respect to forward linkages, it is the emission flows of *Step 1* that reflect the use of fossil energy sources and the character of agricultural production and consumption and upon which policy focuses. Therefore those emissions are subject to great uncertainty and become dominant foci of data, modeling, and analysis.

In 2017, the burning or oxidization of carbon-based fossil fuels and industrial activity (mostly cement production from carbon-based rock) emitted about 36.8 billion tons (gigatons) of carbon dioxide (CO_2) into the atmosphere. Change in land use, mostly deforestation, augmented that by roughly another 4.8 gigatons, for a total of 41.6 gigatons.[40] (The weight of CO_2 is 3.67 times that of the carbon, meaning that these sources added about 11.3 gigatons of carbon that year.)

The emissions of *Step 1* take us to *Step 2* and the accounting for transfers of carbon among the stocks in the atmosphere, oceans, soil, and biomatter. Between 2007 and 2016, the oceans absorbed about 24% of emissions, land sinks took 30%, and the remaining 46% stayed in the atmosphere (adding a net of about 2.5–3.0 ppm annually).[41]

Linking changes in the flows and stocks of greenhouse gases forward to temperatures, precipitation, and broader biophysical impacts (*Steps 3* and *4*) has proven to be a massively complex effort across multiple scientific fields. Since 1880, global surface temperature has risen by about 1°C,[42] but much of the analytical effort has gone into understanding very long-term patterns of global environmental change. For example, drilling for ice cores deep into the polar ice of Antarctica has yielded historical records of up to 2.7 million years,[43] allowing analysis of changes in atmospheric carbon stocks, temperature, and much more over very long periods (Jouzel, 2013). The massive scientific effort continues and is a foundation of the earth systems models (or simplified versions of them) to which IAMs feed greenhouse gas emission flow and stock forecasts.

7.5.2 Atmospheric Carbon Transition

Fig. 7.15 shows the rapid growth in carbon emissions since 1960 and highlights the replacement of high-income countries by middle-income countries (especially China, not separately shown in the figure) as dominant contributors over the last two decades. One of the greatest uncertainties going forward is the degree to which fossil fuels without carbon sequestration will continue to dominate energy use; the downturn in emissions by high-income countries illustrates the shift away from fossil fuels, especially coal, discussed earlier in the energy section of this chapter.

Several factors could lead to peaking in carbon-based fuel use before 2030 and decreasing global emissions thereafter: (1) higher costs of oil and gas extraction, as resources become less

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[40] See http://www.globalcarbonproject.org/carbonbudget/17/highlights.htm.

[41] These numbers change rapidly and measurements vary. See http://www.globalcarbonproject.org/carbonbudget/17/highlights.htm.

[42] See https://climate.nasa.gov/vital-signs/global-temperature/.

[43] See http://www.sciencemag.org/news/2017/08/record-shattering-27-million-year-old-ice-core-reveals-start-ice-ages.

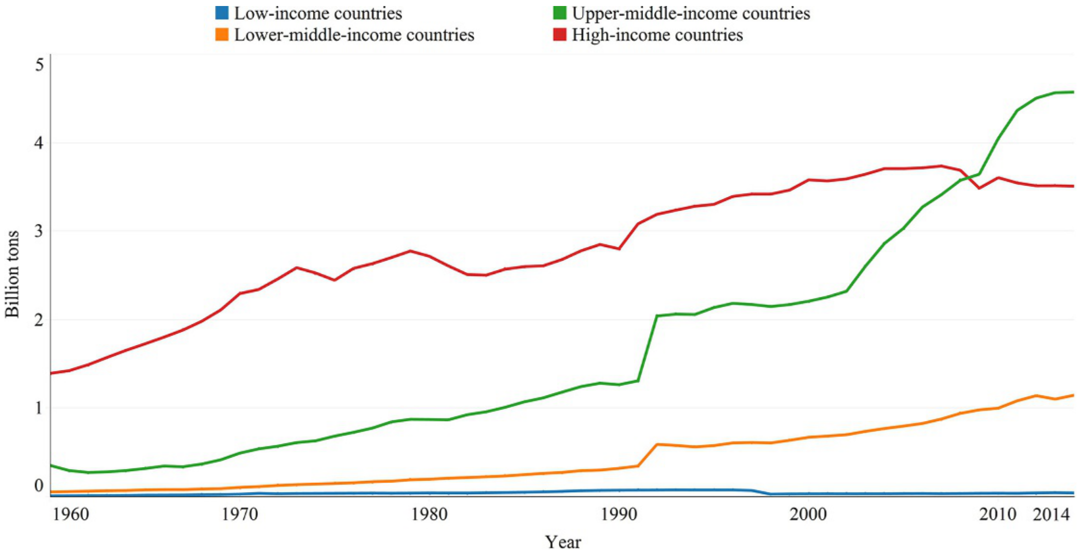

FIG. 7.15 **Carbon emissions by country economy classification from 1960 to 2014.**
Note: Uses World Bank classifications based on gross national income per capita. The transients after 1990 reflect entry of new post-communist states into the database.
Source: IFs Version 7.36, using data from Carbon Dioxide Information Analysis Center.

accessible, (2) monetization or direct regulation of carbon and other emissions, especially from coal, and (3) ongoing reductions in the costs of renewables. Yet the annual average atmospheric stock of carbon dioxide, fed by rising emission flows, has risen exponentially from pre-industrial levels of about 280 ppm[44] to more than 405 ppm in 2017. Almost all of the rise has been in the last half century (see Fig. 7.16), and modest reductions in carbon emissions will not stop it.

7.5.3 Modeling Climate Change

Krey (2014) reviewed the large number of IAMs that represent greenhouse gas emissions, the carbon cycle, and global warming. The IMAGE suite, MESSAGE in interaction with GLOBIOM and other models, GCAM (formerly MiniCAM), and AIM are among the IAMs involved in this work.

The computation of emissions (*Step 1*) involves projecting the level of selected activities times the emissions per unit of activity. Models differ primarily in the extent of activities covered and how they project them. IMAGE represents a very wide range of energy, industrial, and agricultural activities that generate greenhouse gases and other pollutants (Stehfest et al., 2014, pp. 159–170), drawing heavily upon values from EDGAR (Emissions Database for Global Atmospheric Research) with data from 1970. It also looks to LPJmL, linked to IMAGE 3.0 via an interface that facilitates close interaction (Stehfest et al., 2014, p. 175) for emissions associated with land use. Similarly, the MESSAGE system generates projections of carbon and

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[44] See https://climate.nasa.gov/climate_resources/24/.

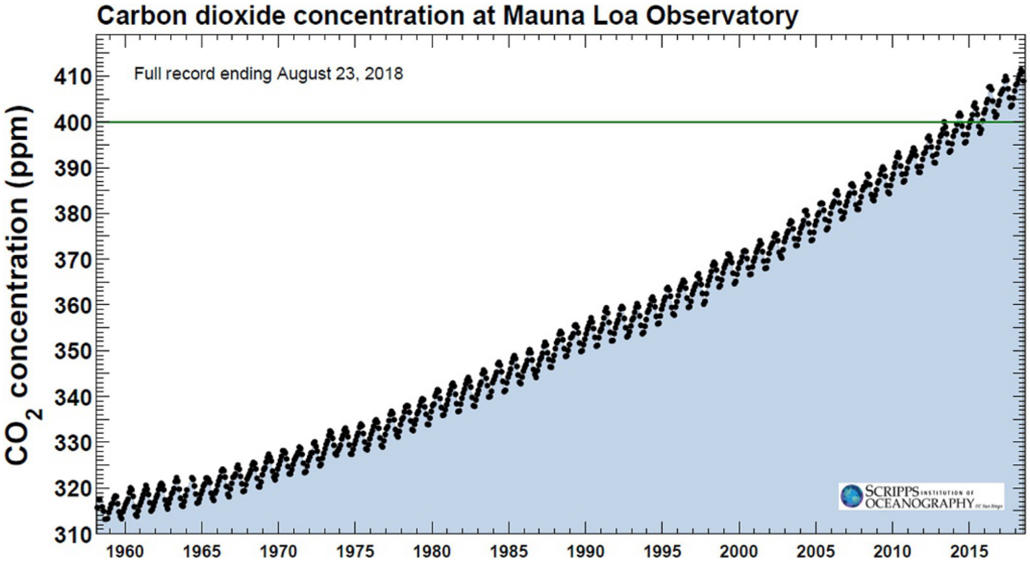

FIG. 7.16 **Atmospheric carbon dioxide concentration measured at Mauna Loa Observatory from 1958 to 2018.** *Note: Measurements at Mauna Loa started in 1958 and reached 400 ppm (ppm) in 2014 for the first time in human history. Source: Reproduced with permission of Scripps Institution of Oceanography at the University of California San Diego; available at https://scripps.ucsd.edu/programs/keelingcurve/wp-content/plugins/sio-bluemoon/graphs/mlo_full_record.pdf.*

other greenhouse gas emissions from detailed energy system representation and draws on GLOBIOM for those from land use/agriculture.

Having emission projections, both IMAGE and MESSAGE (like many, many other IAMs) use the MAGICC 6.0 model to feed those forward to atmospheric concentrations of carbon and other greenhouse gases via representations of the global carbon cycle (Stehfest et al., 2014, pp. 221–225), *Step* 2 in the list presented earlier.

Step 3, translating those concentrations into radiative forcing (the surplus energy in Watts per square meter taken up by the earth due to incremental greenhouse gases) and temperature change is more complicated. The understanding and modeling of that relationship is the focus of some of the most extensive model work in the world. Large-scale general circulation models or global climate models (GCMs) divide the world, including the atmosphere, into three-dimensional grids with interconnected differential equations of change in each box. Those models have developed rapidly since early efforts in the 1950s (for example, Phillips, 1956). Chapter 3 noted that such atmosphere–ocean general circulation models (AOGCMs) can take days to months on supercomputers to project across 100 years.

Alternative Representative Concentration Pathways (RCPs) facilitate consideration of possible radiative forcing (and therefore temperature change) that different concentrations of greenhouse gases may generate. The RCPs help bridge the analysis of the IAM and climate model communities, and they have developed a set of marker RCP scenarios. Those RCPs take the names of numerical values of incremental radiative forcing in the year 2100 relative to pre-industrial levels.

In a special issue of *Climatic Change*, van Vuuren et al. (2011a) provided an overview of the RCPs, including four specific pathway scenarios, each represented in a different IAM.

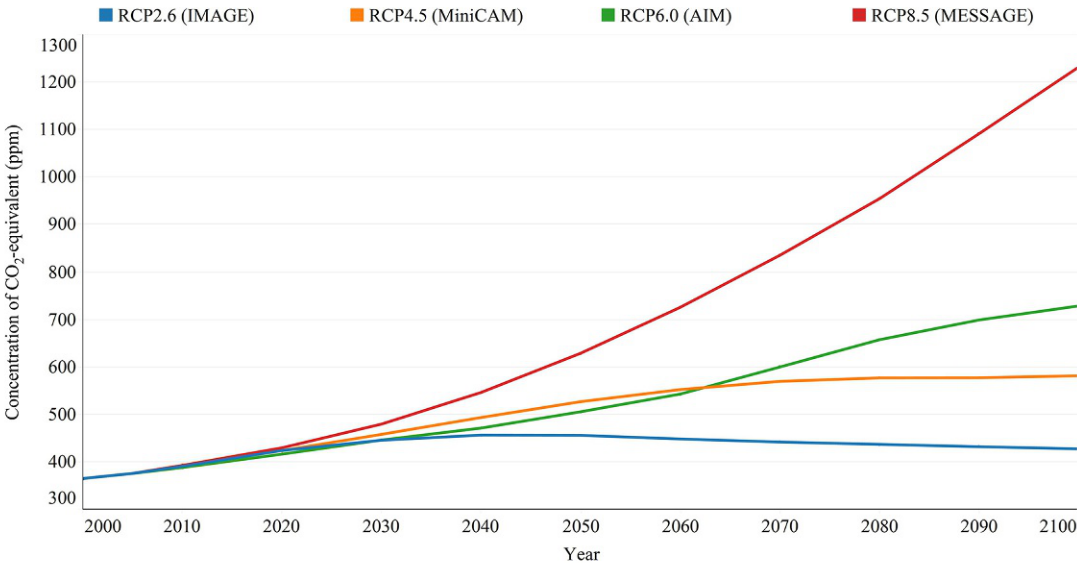

FIG. 7.17 **Alternative representative concentration pathways (RCPs) to 2100.**
Note: For an overview of the RCPs, see van Vuuren et al., 2011a; see also RCP background info at http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome.
Source: IFs project using projections from the RCP database hosted by IIASA at http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=download.

Fig. 7.17 shows those RCPs mapped against the level of carbon dioxide equivalent of all greenhouse gas concentrations that would generate them. Although these four RCPs remain widely used, O'Neill et al. (2016) described the elaboration of four additional RCPs, including RCP1.9, needed to drive a future with only 1.5°C temperature change.

Fortunately, versions of MAGICC also contain representations (albeit simplified ones) of AOGCMs to compute radiative forcing, and geographically detailed warming and precipitation associated with it, given greenhouse gas (GHG) concentration projections. MAGICC thus allows IAMs to replicate the behavior of the AOGCMs in response to emissions, both the concentration of them in the atmosphere and the radiative forcing of that concentration, without the computational cost. Parameters in MAGICC even allow adjustments to replicate the extensive uncertainty within the AOGCMs. (The GCAM system has moved from use of MAGICC for this to Hector, another reduced form representation of the carbon cycle and climate change [Hartin et al., 2015].)

In a comparison of climate change scenarios in IAMs, often using versions of MAGICC, van Vuuren et al. (2011b) found that while the representation by IAMs of the carbon cycle and climate system change lie within the ranges of those from the AOGCMs, those ranges themselves are often very wide. Thus variations in cumulative abatement cost estimates could be trillions of dollars. Other issues of concern for IAMs include the common omission of feedbacks from warming to the carbon cycle itself and the use of specifications that can quickly reduce radiative forcing and temperature when emissions rapidly decline.

Step 4 encompasses a very wide range of potential linkages from climate change to elements of other biophysical systems, such as weather variability, sea level, and plant growth.

The website and work of the World Climate Change Research Programme is a good entry point into efforts and model comparisons related to *Step 4* (as well as to *Step 3*).[45] So, too, is work within the Coupled Model Intercomparison Project (CMIP1–5) and the Inter-Sectoral Impact Model Intercomparison Project.[46] Frequently the models compared are highly focused on a single aspect of climate impact.

Our interest here is primarily in the generally broader IAMs. For instance, the core IMAGE model includes representations of land use and agriculture that provide many points of impact for climate change variables. In addition, IMAGE feeds temperature and precipitation projections to other models. The models linked with IMAGE include GLOBIO for biodiversity in terrestrial systems (with attention to a mean species abundance measure), GLOBIO-Aquatic for biodiversity in freshwater aquatic ecosystems, GLOFRIS (Global Flood Risks with IMAGE Scenarios) for flooding, and USLE (the Universal Soil Loss Equation) for erosion (see chapters in Part 7 of Stehfest et al., 2014 for more information on these models and linkages). Within the IIASA model system, GLOBIOM interacts with MESSAGE in *Step 4*, assessing the impact of energy systems and climate change on land, forest, and water systems, while GAINS can help explore the broader health impacts of pollutants from energy systems.

Many studies have used these and other models to analyze the impact of climate change on agriculture. Illustratively, a study by Nelson et al. (2014) focused on the impact of climate change on agricultural production, using five full-economy models, four partial-economy models (all with agriculture), five crop models, and two grid-cell climate models. The study found that the models, on average, indicated that radiative forcing reaching an end-of-the-century value of 8.5 watts per square meter would reduce crop yield by 17% relative to a scenario without warming. Endogenous responses driven largely by higher prices would lower that reduction to 11%, increase area of crop production by 11%, and reduce consumption by 3%. A significant literature has thus emerged around the impact of climate change on agriculture.

7.5.4 The Carbon Cycle and Global Warming in IFs

IFs represents the same five steps in analysis of global warming and its impact that other IAMs do, but generally more simply. With respect to *Step 1*, annual emission flows, the dominant logic in IFs is the representation of global carbon emissions (*WCARANN*).[47] IFs differentiates the carbon content (***carfueln***), and therefore emissions, from consumption of oil, gas, and coal (*WENP*) without representing any sequestration. Net deforestation in the agricultural model (change in the variable *WFORST*) also endogenously generates a net carbon release.

$$\begin{aligned} WCARANN = {} & WENP_{e=1} * \boldsymbol{carfuel1} + WENP_{e=2} * \boldsymbol{carfuel2} + WENP_{e=3} ** \boldsymbol{carfuel3} \\ & + (WFORST_{t-1} - WFORST) * \boldsymbol{carforst} \end{aligned}$$

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[45] See https://www.wcrp-climate.org/about-wcrp/about-governance.

[46] See https://pcmdi.llnl.gov/mips/cmip5/index.html and https://www.isimip.org/.

[47] In actuality, IFs estimates country-level emissions from fossil fuels and sums to global, but the key logic is global and the presentation here is stylized for simplicity; see the later discussion of limitations.

Moving to *Step 2* of the five steps listed earlier, IFs represents in a simple accounting structure the atmospheric stock changes (*SACarb*) that result over time from the annual emission flows. Emissions augment that stock, and IFs incorporates an exogenous assumption of the net flow of atmospheric carbon to ocean and soil sinks (***carabr***).

$$SACarb = SACarb_{t-1} + WCARANN - \boldsymbol{carabr}$$

where

$$SACarb_{t=1} = \boldsymbol{carinit}$$

The percentage increase in atmospheric carbon (and therefore also carbon dioxide) relative to preindustrial levels (*CO2PER*) depends on the accumulated atmospheric level of carbon (billion tons) relative to the preindustrial level of carbon in the atmosphere by weight (***carprein***).

$$CO2PER = \frac{SACarb - \boldsymbol{carprein}}{\boldsymbol{carprein}} * 100$$

We calculate the atmospheric level of carbon dioxide in parts per million (*CO2PPM*) from this percentage, initializing the pre-industrial level of carbon dioxide in parts per million (***co2prein***).

$$CO2PPM = \boldsymbol{co2prein} + \boldsymbol{co2prein} * \frac{CO2PER}{100}$$

IFs does not include GHGs other than carbon dioxide, so its Base Case scenario of atmospheric CO_2 concentration alone is not truly comparable to other IAMs. Its atmospheric CO_2 path is similar to the RCP4.5 scenario (reaching an atmospheric carbon level near 550 ppm in 2100).[48] However, the omitted GHGs currently add somewhat more than one-fourth more radiative forcing,[49] suggesting that IFs will produce a CO_2 equivalent path closer to RCP6.0 once an effort to include missing GHGs is completed.

Step 3 is the impact that atmospheric carbon level (as a reasonable proxy of overall levels of greenhouse gases, including methane) has on global temperature. As mentioned earlier, the understanding and modeling of that relationship is the focus of some of the most extensive forecasting efforts ever undertaken. Various models project global average temperature increases by the end of the century relative to 1986–2005 roughly in a range from 0.3 °C to 4.8 °C (IPCC, 2014, p. 10). Fig. 7.18 shows the general pattern of projections relating cumulative CO_2 emissions, atmospheric concentration in parts per million (the oval labels), and temperature rise. Based on that pattern, IFs uses a table function to determine the average world temperature (*WTEMP*) in Celsius from the atmospheric carbon dioxide level in parts per million. The IFs function generates about 4 °C total change with a ppm level of 1000, consistent with Fig. 7.18.

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[48] In the scenarios developed within IFs for the GEO-4 project, the concentration levels in 2100 range from 450 to 600 ppm.

[49] Concentrations and radiative forcing associated with additional GHGs are available at http://cdiac.ess-dive.lbl.gov/pns/current_ghg.html in work by T. J. Blasing (DOI: https://doi.org/10.3334/CDIAC/atg.03).

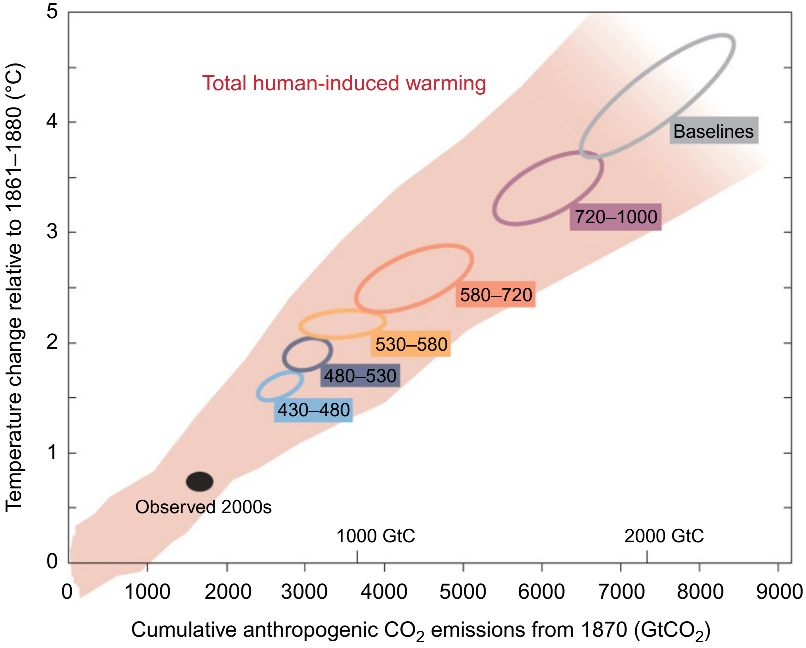

FIG. 7.18 **Relationship of cumulative CO_2 emissions, atmospheric CO_2, and global temperature.**
Note: Global mean surface temperature increase at the time global CO_2 emissions reach a given net cumulative total. Values shown inside graphic are atmospheric parts per million.
Source: Figure SPM.10 (b) from Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R. K. and Meyer, L. (eds.)]. IPCC, Geneva, Switzerland. Reproduced with permission of the IPCC.

$$WTEMP = TableFunc(CO2PPM)$$

AOGCMs do not use global greenhouse gas concentrations to compute global average temperature directly, as in IFs, but rather use them to compute radiative forcing and then temperature for specific area grids around the world, then aggregating those to global temperature change. Because IFs begins with a global temperature change projection and represents countries rather than area grids, it needs to map global temperature to national temperature and precipitation. The approach is related to that of many IAMs that use results from the MAGICC/SCENGEN 5.3v2 (Model for the Assessment of Greenhouse-gas induced Climate Change/Scenario Generator) system of Wigley (2008).[50] Dale Rothman rolled up that system's geographic box representation of the world into countries to allow a mapping of the ratio of country-specific temperature changes to global average temperature change after 1990.[51] Similarly, using MAGICC coefficients for temperature and precipitation change, he prepared a set of coefficients for country-specific percentage changes in precipitation caused

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[50] See MAGICC/SCENGEN model website at http://www.cgd.ucar.edu/cas/wigley/magicc/.

[51] Using Gridded Population of the World (GPW) v3 from http://sedac.ciesin.columbia.edu/data/collection/gpw-v3.

by global change in temperature; namely, change at the country level is one plus the coefficient raised to the power of the degrees of change in global temperature. The MAGICC coefficients for temperature and precipitation change represent averages from 18 AOGCMs.

Step 4 involves calculating the broader biophysical impacts of temperature and/or precipitation changes. In IFs, the only (but important) such impact of the national temperature and precipitation changes represented is on country-specific crop yields. The earlier discussion of agriculture modeling (Section 7.1.4) laid out the process of doing so in IFs.

Step 5 is the linkage of biophysical impacts back to human systems. The explication of the agricultural model explained how climate change affects agricultural yields, but yield has further impact on nutrition and economic growth, and both of those have many broader developmental implications in IFs. The next chapter discusses the addition to IFs of a formulation linking climate change directly to economic growth. As in some other IAMs, biophysical representations (beyond climate change), such as the use of solid fuels for cooking or the level of urban air pollution, also have further human and social system impacts in IFs (discussed with the health model in Section 5.2.4.3).

7.5.5 Limitations

Limitations of the approach in IFs include representation of greenhouse emissions only with CO_2 release from fossil fuels and deforestation. It would be quite easy to add carbon from cement production and methane from livestock (mostly cattle) flatulence. Other gases and sources would be more difficult to represent.

Another limitation is the structure of the IFs energy model as a supply-side energy model that represents demand in total only, not by energy form. Thus while IFs calculations from the production side of carbon emissions from fossil fuels can appropriately represent the global pattern, it is complicated to estimate national levels, which should be tied instead to consumption. Currently, assumptions concerning the fossil share of energy usage help calculate a rough estimate of emissions by country.

The use of a country-based model instead of a grid-based one obviously complicates the forward analysis of greenhouse gas concentrations not only to the calculation of temperature and precipitation changes but also onward to the impact on agriculture (and potentially to diseases such as malaria). A grid-based representation of land and its production would allow a more refined analysis of warming's impact.

7.5.6 Comparative Scenarios

The third assessment of the Intergovernmental Panel on Climate Change included an influential comparative study of projections of global carbon dioxide emissions. The study showed projections of annual net emissions in 2100 ranging from a negative value to a factor of 10 beyond the value in 1990 (IPCC, 2000, p. 7), although scenarios with policy interventions held that level below a factor of three. Overlaid on that full database of study results, Nebojša Nakićenović and colleagues created scenarios organized in six sets (IPCC, 2000, pp. 4–5); these became known as the SRES (Special Report on Emission Scenarios) scenarios and used rather cryptic labels, such as A1FI and B1. The 2100 projected emission levels from those ranged from a bit less than in 1990 to a factor of about six times that level.

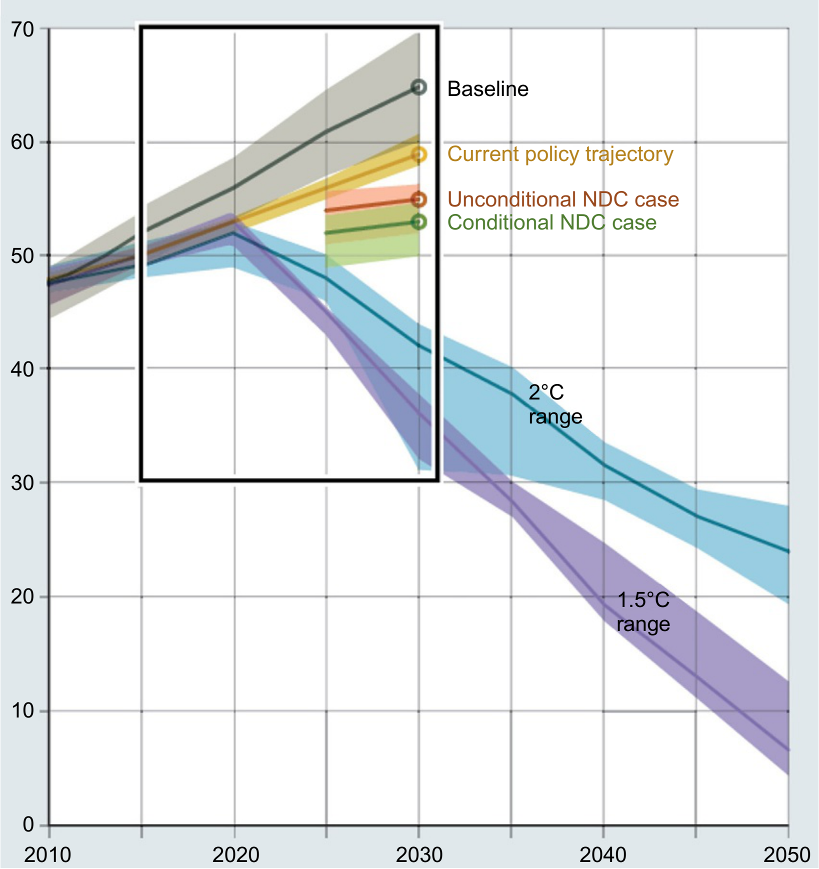

FIG. 7.19 **Alternative global growth patterns of annual carbon dioxide equivalent emissions and associated temperature change.**

Note: Y-axis units are annual gigatons of carbon dioxide equivalent from all greenhouse gas emissions; ranges reflect from the 20th to the 80th percentiles of confidence intervals. Rogelj et al. (2016) describe the scenarios and the methodology of developing the figure from multiple sources.

Source: Lower right portion of Fig. 3.1 (p. 15) from the United Nations Environment Programme Emissions Gap Report 2017 at https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf. Reproduced with permission of the United Nations Environment Programme.

There has been much subsequent work on alternative futures of greenhouse gas emissions from energy and other sources, some of it reported in the annual emission gap reports of the United Nations Environment Programme (UNEP). Fig. 7.19 shows a graphic (UNEP, 2017, p. 15) representing a baseline trajectory, shifts of that pathway that existing policy or policy initiatives might make, and alternative paths needed to attain global temperature goals, such as holding change below 1.5° or 2 °C. Using an integrated set of unconditional and conditional pledges already undertaken or planned, the UNEP figure facilitates understanding of the impact of what countries have indicated under the Paris Agreement to be their Nationally Determined Contributions (NDCs) to emissions control. It also shows the additional reductions needed to meet targets.

The portrayal in Fig. 7.19 is a relative of the wedge analysis approach to identifying policy leverage points or "handles" for making progress against emissions (Davis et al., 2013; Pacala and Socolow, 2004). It is quite obvious that the 1.5° and 2 °C scenarios would require very substantial changes in behavior—such as greater energy efficiency, reduction in the share of fossil fuels in the energy supply mix, control of methane releases, and significant other measures—well before 2050. In fact, even the NDC scenarios would require important interventions. The low emissions scenarios thus stand in rather sharp contrast to almost all of the SSP baseline scenarios that were discussed in Section 7.2.5 with respect to energy projections with their high fossil fuel use. Even the baseline scenario for SSP1 (the least emitting) produces carbon emissions by the end of century that are still above the level in 2000 (Bauer et al., 2017, p. 326, Figure 8). Reinforcing (and actually underlying) the picture provided by Fig. 7.19, the SSP analysis around energy futures found that to generate the RCP associated with the 1.5 °C future, emissions would have to peak soon and decline rapidly.

As noted in the energy discussion earlier in this chapter, the IFs Base Case exhibits considerable optimism concerning nonrenewable energy production growth and the role of natural gas among the fossil fuels. Even it, however, anticipates peaking of annual global carbon emissions near 2040 at a level about 22% higher than that of 2010, well above the pattern of the 2° climate change scenario in Fig. 7.19.[52] And carbon fuel use continues through the century in the IFs Base Case, with emissions in 2100 still nearly two thirds of today's level. That pushes global temperatures in 2100 to about 3 °C higher than preindustrial levels in the IFs Base Case. In short, bending the emissions curve soon and sharply will be extremely difficult (if even possible).

7.6 WATER SYSTEMS

Globally, human systems withdraw and use about 9% of all annually renewable water supplies. Withdrawals do not include water in the form of precipitation that directly supports crop production or rainfall in forests, both of which clearly provide services to humanity. Nor does it include river flows of unused water to the ocean. The withdrawals are extremely uneven within and across countries. Twenty-three countries withdraw more than 100% of renewable supplies (IFs project analysis) therefore reusing water or drawing down stocks. Agriculture places the greatest demand upon supplies, and accounts for 70% of all water that we withdraw from the natural environment (Stehfest et al., 2014, p. 197). Obviously, our use of water heavily impacts natural systems, as well as being a potential constraint on developmental systems.

7.6.1 Concepts, Structures, and Data

Countries are the dominant large-scale units of human organization globally and they gather and organize most human and social development data on variables such as

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[52] The trend scenario of van Vuuren and Kok (2012, 37) shows a steady rise to about 80 gigatons of carbon dioxide equivalent in 2050 from about 50 currently, a climb of about 60%.

education, health, income, government and finance. Thus the spatial basis for thinking about the future of human and social development is almost always countries or their geopolitical subunits. This is often true also with respect to human systems that interact closely with natural ones, such as agriculture (especially food provision), energy, and infrastructure.

Yet as we move to more direct attention to biophysical systems and their two-way relationship with human and social ones, that attention to countries becomes problematic —neither carbon nor water obey visa requirements or trade rules of origin in their movements within and across borders. As with the production side of agriculture, water supply or hydrology modeling is often done in close association with representation of more highly elaborated spatial systems.

Spatially, the supply side of water modeling often uses grid-based geographical representations (frequently 0.5° squares), sometimes in combination with representation of water basins. Fairly standard supply categories include renewable surface water, renewable ground water, nonrenewable (or very slowly renewing) ground water, recycled water, and water from desalination.

On the demand side, Wada et al. (2016), like many other analysts, differentiated agriculture (separating livestock[53] and irrigation use), industry (differentiating energy extraction, electricity production, and manufacturing use), household use (or more generally the domestic sector), and environmental flow requirements (protecting the ecosystem services of water flow). Data regarding demand are sometimes grid-based, but also often by country.

To understand the future of water systems, there is value in combining spatially based hydrological modeling for the supply side (that can also connect with spatially based land-use/agricultural models) with demand-side formulations so as to build equilibration processes that link supply and demand. Demand might draw either on geopolitically representative demand formulations or spatial representations, with the latter especially for agriculture via linked land-use/agricultural modeling. Putting demand and supply together, much analysis shows rapidly growing demand trajectories that outstrip supplies (including nonrenewable ones). It is also important to know, however, how the combined supply-consumption system might evolve, recognizing the role of changing prices and usage patterns. That kind of supply-constrained modeling and analysis is now beginning to emerge.

A common source of water data is the FAO’s AQUASTAT with country level data on a wide variety of demand and supply variables. On the geographically elaborated supply side, sources are much more disparate and linked to water supply type. For example, Kim et al. (2016) identified a variety of the sources used in the GCAM hydrology model, including the work by Beck et al. (2013) on base streamflow in 3394 catchments worldwide.

7.6.2 Water Transitions

Wada et al. (2016, 175) pointed out that increasing food demand and higher standards of living are key drivers of rising water withdrawals, which grew globally by nearly a factor of

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[53] Whereas production of one kilogram of rice requires, on average, 1900–5000 L of water (versus 500–1500 for potatoes), a kilogram of chicken requires 3500–5700 L and one of beef uses 15,000–70,000 (Kumar, 2013, Table 2, using estimates from the Pacific Institute). Still, aggregate livestock-based demand for water tends to be small compared to irrigation needs, with exceptions such as Botswana.

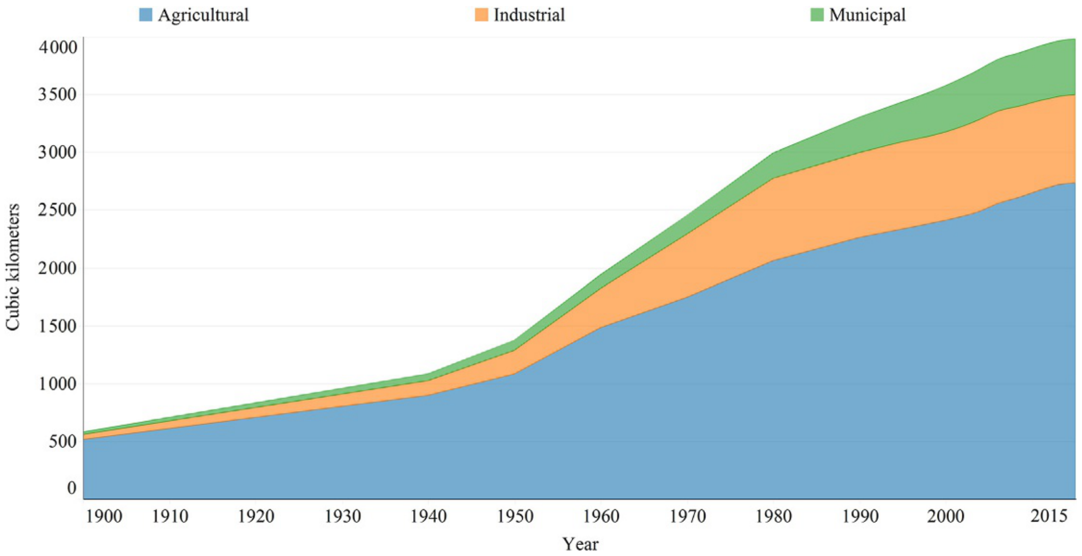

FIG. 7.20 **Global water withdrawal by sector from 1900 to 2015.**
Note: Values from FAO AQUASTAT data started in 1980 for agricultural withdrawals and in 1995 for industrial and municipal withdrawals; earlier values are from Shiklomanov (2000, 24). Both FAO and Shiklomanov used incomplete data from many sources; holes in country level data filled by interpolation with IFs.
Source: Figure through 2010 available on the Food and Agriculture Organization of the United Nations (FAO) AQUASTAT website at http://www.fao.org/nr/water/aquastat/water_use/image/WithTimeNoEvap_eng.pdf; figure extended through 2015 by IFs project using more recent AQUASTAT data downloaded March 1, 2018 from http://www.fao.org/nr/water/aquastat/water_use/index.stm.

eight (to 4000 cubic kilometers per year) between 1900 and 2010. Fig. 7.20 shows that growth and a sectoral breakdown; domestic use of about 18% and industrial use of about 12% augment the 70% share of agriculture. The figure also clearly shows an S-shaped pattern across time as growth in water withdrawals transitioned from acceleration to deceleration in the last half of the previous century, in significant part due to increasing supply constraint. Whereas land equipped for irrigation expanded globally at nearly 5% annually between the 1950s and 1980s, its more recent growth has been less than 1% each year (Wada et al., 2013, p. 4626).

The global picture of what has been happening with respect to water systems conceals tremendous geographic variation. One way of seeing that variation is to consider renewable surface and ground water resources per capita. A common characterization identifies *water stress* when renewable availability is less than 1700 cubic meters per person and *water scarcity* when availability drops below 1000 cubic meters per person (see Fig. 7.21 for United Nations subregions that fall into these categories).[54] Further, average rates of total water availability in physically diverse regions can mask areas of great water scarcity or stress at country, basin, and local levels, even in regions like Northern Europe (5600 average cubic meters per person) and Central Africa (with 9200).

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[54] See http://www.un.org/waterforlifedecade/scarcity.shtml.

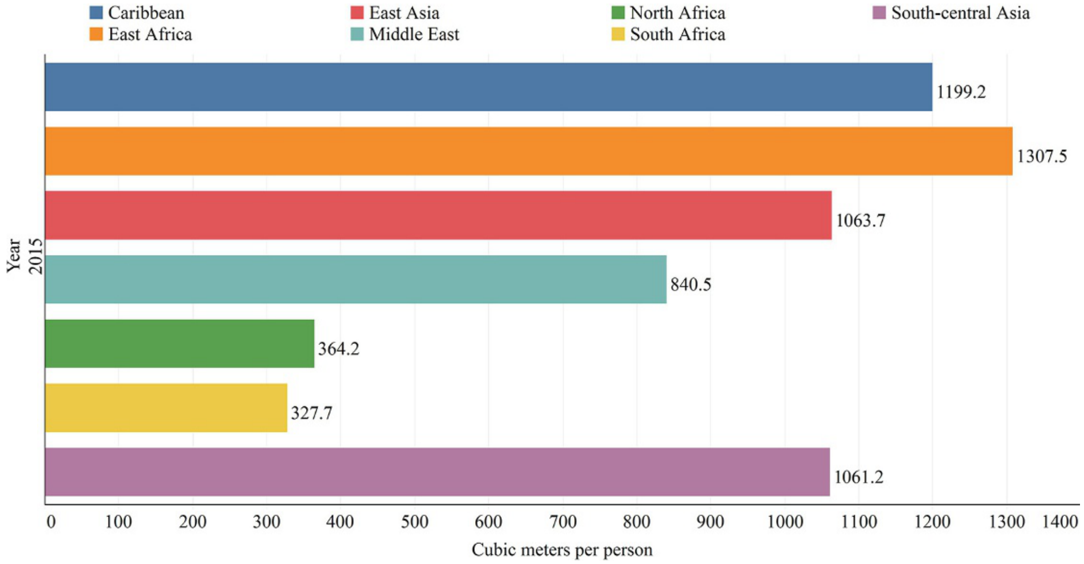

FIG. 7.21 **Regional variation in renewable and exploitable surface and groundwater resources per capita in 2015.**

Note: Shows the United Nations subregions with less than 1700 cubic meters of surface and groundwater resources per capita. Source: IFs Version 7.36, using data from the Food and Agriculture Organization's AQUASTAT database.

Fig. 7.21, with its focus on renewable surface and groundwater resources, and thus sustainable flows, does not convey a full picture. A major water issue around the world is withdrawals from aquifers in excess of their recharge rates, thereby drawing down stocks. In many places, including but by no means limited to much of North Africa and the Middle East, the aquifers contain water dating back centuries or millennia and have near zero recharge rates. Any such fossil water use obviously is unsustainable, regardless of the usage flow rate. Unfortunately, longitudinal and even contemporary data on overuse of renewable and nonrenewable groundwater are extremely patchy, not allowing us to see stock patterns clearly. Moreover, modeling of them is in its infancy.

7.6.3 Modeling Water Systems

The Water Model Intercomparison Project (WaterMIP) facilitates analysis of multiple global water models. So, too, did the 2007–2011 European Union-funded WATCH (Water and Global Change) project, which interfaced with WaterMIP.[55] Additionally, Chen et al. (2011) and Flörke and Eisner (2011) identified and described major water modeling projects, including WaterGAP at the University of Kassel. More recently, Wada et al. (2016) did a comparative analysis of global water futures using three different global water models (discussed later), following an earlier comparative analysis of seven global hydrological models with respect to the impact of climate change on irrigation (Wada et al., 2013).

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[55] See http://www.eu-watch.org/watermip.

As stated previously, much water modeling involves hydrology models with a special focus on the supply side and with spatial representation, either gridded or by water basin, or both (Devi et al., 2015). I have already referred in this chapter, for instance, to the IMAGE use of LPJmL (Lund-Potsdam-Jena managed Land), which "simulates vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems."[56] LPJmL uses 0.5-degree grid cells and outputs can be generated for daily, monthly, or annual periods; it represents 13 crop functional types (11 arable crops and two managed grass types) and allows historical simulations from 1901 to 2000.

One of the important uses of LPJmL is analysis of the ability of water supply to meet demand in water basins. This has encouraged the development of a river routing module within LPJmL to address issues of water scarcity (Bondeau et al., 2007, p. 701). One of the challenges is that no appropriate data were available for fossil groundwater resources.

In addition to the spatially specific character of water systems, there is also much reason for looking at them through the lens of countries. With a focus on the demand side, Fader et al. (2011) explored the virtual trade (i.e., embedded with traded food and used in its production) of water, elaborating the associated water footprints of importing countries.

At the country level we want models and analyses that help us understand the aggregate relationships of demand and supply, including the possibility of growing water scarcity and its consequences. Bridging country and grid-level perspectives is IMPACT, which earlier discussion of agriculture system modeling introduced in Section 7.1.3. IMPACT has three water models in its associated system (Robinson et al., 2015, p. 13, 30). A hydrology model represents snowmelt and runoff to river basins and groundwater as well as renewable surface water, but not explicitly fossil water. A water basin model represents transboundary systems and has water demand formulations that differentiate domestic (municipal and rural), industrial, livestock, and irrigation categories. And finally, a water-stress model computes potential water constraints upon agriculture and feeds production implications back to IMPACT.

In the context of the Water Futures and Solutions (WFaS) initiative, Wada et al. (2016, p. 176) presented information on three global water models (WaterGAP, H08, and PCR-GLOBWB) that combine attention to supply and demand across multiple major categories, often at both spatially detailed and country levels. Those features facilitated broad analysis of water futures to be discussed in comparative analysis later, including scenarios tied to the SSPs and the RCPs. Here I focus on the models themselves, all three of which produced analyses associated with the SSPs.

Work by Alcamo et al. (2003a, 2003b), updated in Flörke et al. (2013), elaborated WaterGAP, the earliest of the three water models listed previously. WaterGAP has three main components (Wada et al., 2016, pp. 195–196): (1) five sectoral water use models (irrigation, livestock, thermal electricity, other industry, and households and small businesses), (2) a global hydrology model for the terrestrial water cycle (including surface and groundwater with attention to water basins), and (3) water quality. Population and usage intensity drive domestic demand with sigmoid behavior, thereby reflecting structural and technological change (including efficiency); thermal electricity production drives its water demand in

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[56] See https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml.

similar fashion. Total countrywide water usage estimates are mapped to grid cells according to population density and, for industrial use, to urban population.

H08, the second of the three models listed previously, represents municipal demand plus industrial use (driven by, and not separated from, electricity production). Scenarios around water usage for irrigation are drawn from several other models for the purposes of its SSP analysis (Hanasaki et al., 2013a, pp. 2378–2380); it looks especially to the CROPWAT model (Smith, 1992) for insight on irrigation water demand. On the supply side, H08 represents water resources and human management (Hanasaki et al., 2013b, p. 2394). It builds on six submodels that track land surface hydrology, river routing, crop growth, reservoir operation (the 507 largest), water abstraction, and environmental flow requirements. Industrial water demand is mapped to gridded population distribution.

Wada et al. (2014) documented the third model used in the SSP analysis, namely PCR-GLOBWB, with extensions to connect water withdrawals and consumption with macro hydrology modeling. PCR-GLOBWB represents irrigation (differentiating paddy and non-paddy), livestock, industrial, and household consumption. GDP, total electricity production, and total energy consumption drive industrial water demand, with modification for efficiency change, and that demand is mapped to urban population distribution (Wada et al., 2016, p. 182). The domestic demand formulation includes economic development and technological change. The hydrology model is gridded and structured for daily analysis. It includes representation of reservoirs in its mapping of surface flows and groundwater withdrawals and it is set up for water basin analysis. The model returns a large share of water withdrawn from surface and groundwater sources to river systems, and that groundwater share of water withdrawal and use varies by region and time (Wada et al., 2014, p. 26), establishing important aspects of a demand-supply interconnection. For example, whereas in Europe a fairly stable 30% of withdrawals are groundwater, in Western Asia groundwater withdrawals have tripled between 1979 and 2010 to about 70% of the total.

Addressing the need for feedbacks from constrained water resources to future patterns of water demand and supply, Kim et al. (2016) used GCAM to look at two-way relationships across 14 geopolitical regions, 151 agricultural-ecological zones, and 235 major river basins. The authors represented agricultural (12 crop types), energy, industrial, and municipal demand, and gridded renewable water, nonrenewable groundwater and desalinated supply sources in a dynamic, recursive system with five-year time steps from 2005 through 2100, keeping demand and supply in equilibrium at the basin level.

To address demand and supply interaction in forecasting, it is important to represent the impact of depletion of nonrenewable groundwater. In support of such analysis, Wada et al. (2010) estimated nonrenewable groundwater depletion at 309 cubic kilometers per year (42% of all groundwater withdrawals), while other estimates range as high as 800 cubic kilometers (Kim et al., 2016, p. 221; see also Wada, 2016). As in energy modeling, however, there is an alternative to representing resource stocks and their use over time explicitly. For instance, GCAM does not use a McKelvey box-like estimation of ultimate fossil water resources, but rather marginal cost curves that rise with cumulative usage; scenarios simulate alternative cost patterns and thus, implicitly, resource availability. The model represents desalinated water to be infinitely available at exogenously specified cost and not to be used for irrigation. The three sources (renewable water, fossil water, and desalinated water) are nested in a logit structure in which they compete to satisfy demand with costs and prices rising to generate equilibrium.

7.6.4 Water in IFs[57]

Although it does not have a grid-based structure, the water model of IFs represents demand, supply, and equilibration. That equilibration has implications for irrigation and agricultural yields that were discussed earlier.

Relying on a common segmentation of demand, IFs has separate formulations for municipal, industrial, and agricultural water demand (*WATDEMAND*). At the municipal level, water demand per capita (*WaterDemandPC*), increases with GDP per capita at PPP (*GDPPCP*) and safe (piped) water availability (*WATSAFE*), but decreases with urbanization level, algorithmically smoothed to limit shocks (*UrbanPercentSmooth*).

$$WATDEMAND_{r,wd=municipal} = WatDemandPC_{r,wd=municipal} \times POPURBAN_r$$

where

$$\begin{aligned} WatDemandPC_{r,wd=municipal} = {} & x_1(\ln(GDPPCP_r)) + x_2\left(\ln\left(WATSAFE_{r,sw=piped}\right)\right) \\ & - x_3(\ln(UrbanPercentSmooth_r)) \end{aligned}$$

Electricity production currently accounts for a very large portion of industrial water use, but it will not in the long term. While electricity production will continue to grow substantially across the century, more and more of it will come from renewable sources, requiring minimal water for operation relative to the cooling needs associated with electricity generation from fossil fuel or nuclear plants. We therefore segment industrial water demand, making it a sum of that for electricity from fossil and nuclear sources and that associated with growth of the manufacturing sector. We have not tied energy-sector water demand to hydroelectric power, however, where some reservoir evaporation should be added to demand. Nor have we accounted separately for water injection in fossil fuel production.

$$\begin{aligned} IndustrialWaterDemandforElectricity_r = {} & ActualWaterUsePerkWh_r \\ & \times NonRenewablePowerGeneration_r \end{aligned}$$

where

ActualWaterUsePerkWh is the amount of water used per kWh and is a function of both the level of water scarcity in the country and the GDP per capita at PPP, and *NonRenewablePowerGeneration* is the total electricity production calculated in the infrastructure model (INFRAELECPROD) minus the production of electricity from new renewable sources (ENP) in the energy model

The manufacturing portion of industrial water demand responds to the growth of the manufacturing sector with an elasticity well below one because of increasing efficiencies of use. The global value in IFs reflects those from country studies.

$$\begin{aligned} & IndustrialWaterDemandforManufacturing_{r,wd=manufacturing,r,t} \\ & = IndustrialWaterDemandforManufacturing_{r,wd} \end{aligned}$$

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[57] Steve Hedden has led the development of water modeling within IFs.

$$= manufacturing, t-1 \times \left[\frac{VADD_{r,s=manufacturing,t}}{VADD_{r,s=manufacturing,t-1}}\right]^{0.45}$$

where

industrial water demand in the first year is calculated by subtracting electricity water demand from total industrial water demand

With respect to agricultural demand for water, we represent only irrigation use in *WATDEM* (not animal usage).

$$WATDEMAND_{r,wd=agriculture} = WaterPerHA_r * LANDIRAREAACTUAL_r$$

where

WaterPerHA is the amount of water required per hectare of irrigated land and
LANDIRAREAACTUAL is the area of land irrigated

The efficiency of irrigation (*WaterPerHA*) is directly affected by water price, but is not allowed to decrease by more than 2% per year. The area of irrigated land is driven by the area of land equipped for irrigation (*LANDIRAREAEQUIP*) as computed in the infrastructure model, a saturation level of 'irrigable land' (*LANDIRAREASAT*), water price, food price, precipitation, and a historical growth rate; it is constrained by government expenditures from the economic model.

The supply side represents surface water withdrawal, renewable groundwater withdrawal, nonrenewable (fossil) groundwater withdrawal, direct use of treated wastewater, and desalinated water. Treated wastewater (secondary water) that is not directly reused is added to surface water yield.

Supply magnitudes that are especially likely to change over time are (1) treated and reused wastewater (IFs addresses this in the infrastructure model), (2) desalinated water (which IFs represents in terms of historical growth patterns, constrained by assumptions of future potential), and (3) withdrawals from nonrenewable resources. IFs uses data available from AQUASTAT to initialize the first two of these.

The most challenging component on the supply side is the use of nonrenewable ground water because data on its remaining volume and change in its annual usage are not readily available. We drew on various estimates of fossil water supplies, including those from the FAO, UNESCO, and MacDonald et al. (2012). Data on overuse of rechargeable aquifers are somewhat useful, but generally consist of rates of annual decline in the water table, not remaining stock volume. Nonetheless, we bound future withdrawal by estimated remaining volume. To assure asymptotic approach to maximum withdrawals and smooth decline thereafter, we reduce withdrawals when they exceed one-twenty-fifth of remaining volume.

$$WATERWITHDRAWAL_{r,ws=fossil,t+1}$$

$$= \text{Min}\left(WATERWITHDRAWAL_{r,ws=fossil,t} * 1.01, \frac{WATRESFOSSIL_r}{25}\right)$$

Given water demand and supply, our formulations move to equilibration. As in other IFs models, those formulations use a feedback system tied both to distance from equilibrium and rates of change in that distance (our PID controller approach; see again Section 6.1.4.3). The controller uses that balance of aggregate demand and supply to change a country-specific water price index over time; that variable feeds back to all supply and demand terms with elasticities that have been drawn as possible from the literature.

7.6.5 Limitations

The absence of grid-based and/or watershed-based representation of water supply in IFs is especially notable, and grid-based demand would also be useful. Structurally, it would also be useful to break out livestock-related water demand from total agricultural withdrawals. Also related to the accounting system structure, the IFs system does not represent the direct use of non-treated wastewater (which is, however, relatively minor). Further, the model represents "backflows" from demand to supply in the municipal sector, but not in agricultural or industrial use. Most generally, the distinction between demand and withdrawals is not made consistently or clearly.

On the data side, the IFs project has struggled with representation of ground water, especially fossil resources, as have other model projects. Further, the parameterization of demand and supply responses to price change is at an early stage in IFs modeling, as in other efforts.

With respect to causal dynamics, a significant limitation is the absence of linkage from climate change to irrigation water demand.

7.6.6 Comparative Scenarios

Long-term water demand scenarios are not numerous. Using the IMAGE suite, Stehfest et al. (2014, pp. 201–203) provided a baseline global projection of water demand rising well above 6000 cubic kilometers by 2050. IMAGE-LPJmL produced the agricultural water demand, but household and manufacturing sector demand used data and algorithms from the WaterGAP model (Alcamo et al., 2003a) and electricity sector demand was tied to Davies et al. (2013).

The fourth Global Environment Outlook (GEO-4) used the WaterGAP model for projections of water demand in four scenarios that the GEO report elaborated more generally (Rothman et al., 2007). The range of uncertainty around water demand was very large already by 2050. There was very limited change in total demand by 2050 relative to 2000 in both the Policy First and Sustainability First scenarios, leaving the global total near 4000 cubic kilometers annually. The Markets First scenario of GEO-4 was essentially a base case scenario and was very close to the baseline value in 2050 of IMAGE at about 6000 cubic kilometers annually; in Security First it rose to 7000.

In their analysis of the SSP1, SSP2, and SSP3 scenarios (see Section 3.3.2.1) using the three models discussed earlier (WaterGAP, H08, and PCR-GLOBWB), Wada et al. (2016) could not provide projections for agricultural demand because the SSP stories had not been quantitatively elaborated for land use, including irrigated area, or for livestock futures (Wada et al., 2016, p. 180, 186). Other limitations were some differences in initial data for the country-sourced WaterGAP model relative to the AQUASTAT data used for H08 and PCR-GLOBWB, and the failure of the latter two models to disaggregate the industrial sector into thermal electricity, manufacturing, and other subsectors. However, the study was able to use the models to comparatively project industrial water demand across the three SSP scenarios. In SSP2, the Middle of the Road scenario, increases in industrial water withdrawals between 2000 and 2050 varied considerably across the three water models, from 70% to 120%, with those from WaterGAP being the highest (Wada et al., 2016, p. 187). In a different study using seven global hydrological models and looking at representative concentration pathway scenarios, Wada et al. (2013, 4629) estimated that by the end of the century irrigation water demand would increase by more than 10% on most irrigated regions with the RCP4.5 scenario, and that with RCP8.5 the rise would exceed 25% in many heavily irrigated areas.

Wada and Bierkens (2014) used a somewhat simpler methodology to project total global water withdrawals (usage from all sources) through 2100. Their motivating concern was to reconcile increasing water consumption and withdrawals with the current use of nonrenewable and nonsustainable resources, and their approach was to develop a blue water sustainability index. Their grid-based analysis drew on PCR-GLOBSWB. Global water withdrawals grew to more than 6000 cubic kilometers in the second half of the century and then stabilized.

Kim et al. (2016) used GCAM to explore water use and availability scenarios. GCAM has the triple advantage of extending through 2100, representing all sectors of demand, and equilibrating demand and supply. Interestingly, even in an unconstrained (nonequilibrated) baseline scenario, Kim et al. projected that water demand will level off in mid-century near 6000 cubic kilometers per year (as in Wada and Bierkens, 2014). In their supply constrained alternative base case, water withdrawals peak at 5500 cubic kilometers per year (km^3 years^{-1}) by 2050, and fall to 5000 by 2100. Irrigation usage declines the most in the supply constrained baseline case relative to the unconstrained baseline forecast, falling 20% by 2100 (Kim et al., 2016, p. 224). Southeast Asia and the Middle East show the greatest relative declines, and drawdown of nonrenewable ground water (with increasing costs) is a significant driver. Desalinated supplies grow globally by more than an order of magnitude in the supply constrained scenario. See Fig. 7.22 for the GCAM global total projections of water withdrawals. While changes in water availability and price have costs for agricultural use in GCAM, changes in patterns of food trade allow more water abundant regions to offset such impacts considerably, facilitating the elaboration of the supply constrained base case.

In Fig. 7.22, the equilibrated Base Case scenario of IFs produces a gradual slowing of global water withdrawal growth across the century, reaching about 5800 cubic kilometers at its end, a value that is between the water-unconstrained and water-constrained levels from the GCAM analysis. In the case of IFs, such slowing is apparent in all demand sectors (especially agriculture), and in addition to supply constraint is related to peaking of total population, slowing of economic growth, growth in the non-thermal share of electricity, and diminishing opportunities for expansion of irrigation (with roughly stable total land devoted to crops). Municipal demand, driven by ongoing urbanization and some convergence of global incomes, shows the least slowing (see Fig. 7.23).

Overall, some considerable headroom remains for understanding possible water withdrawals in the future and for analyzing the further impact that water constraints will have on human systems.

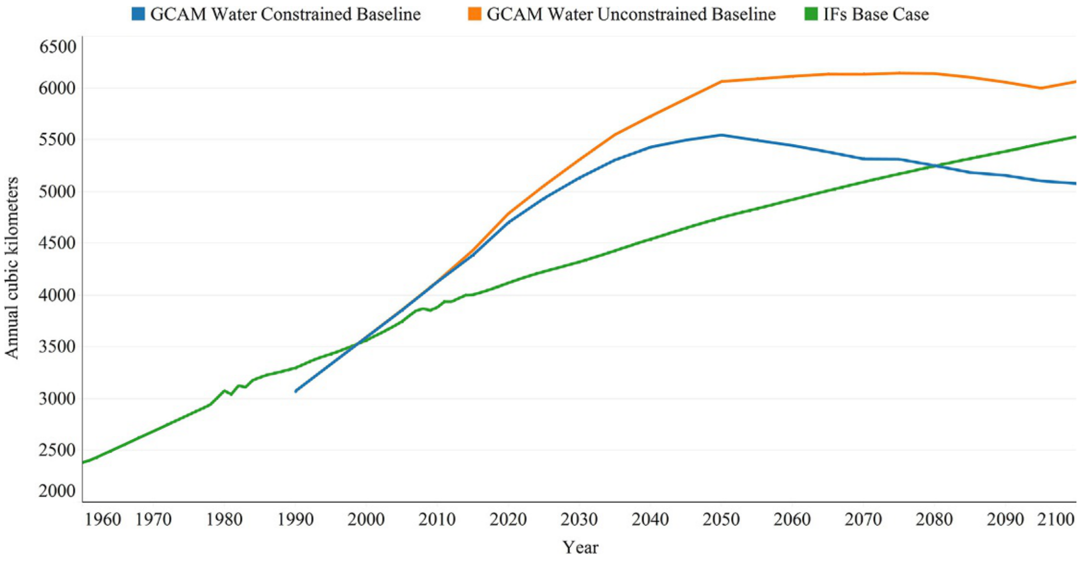

FIG. 7.22 Global water withdrawals in Global Change Assessment Model (GCAM) scenarios and IFs Base Case to 2100, with history from 1960.
Note: See Kim et al., 2016 for description of the GCAM scenarios. IFs Base Case is supply constrained. Because the historical series is very sparse, estimation was used to fill holes and 5 years with especially skimpy data were removed.
Source: Author, using IFs Version 7.36 and historical data from the Food and Agriculture Organization's AQUASTAT database; values for the GCAM scenarios generously provided by Son H. Kim.

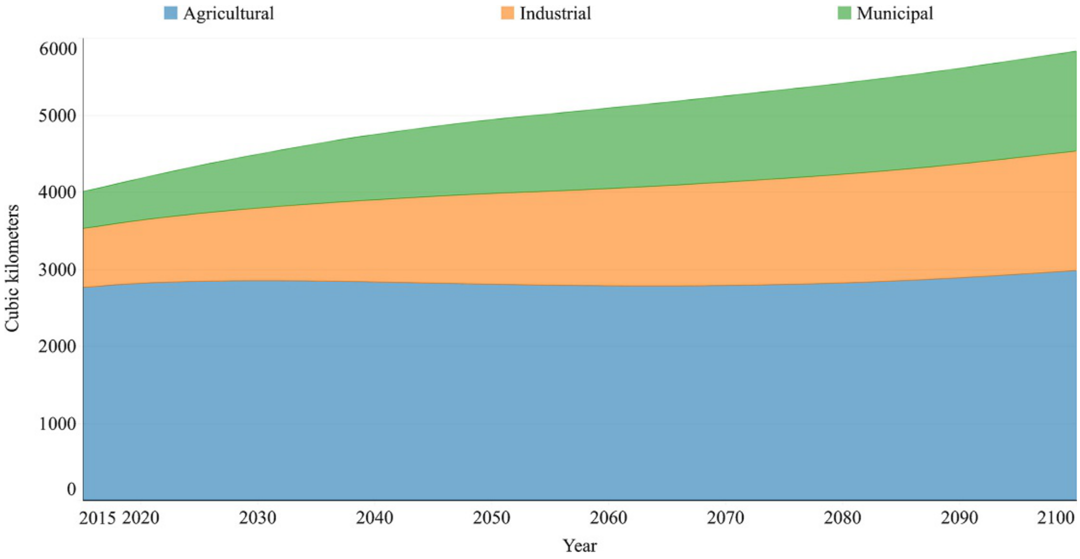

FIG. 7.23 Global water withdrawals by sector in the IFs Base Case scenario to 2100.
Source: IFs Version 7.36, initialized with data from the Food and Agriculture Organization's AQUASTAT database.

7.7 CONCLUSION

This chapter identified agriculture/food, energy, and infrastructure as three key human systems that interact with biophysical ones, and it discussed their modeling. It then directed attention to environmental change from those systems, notably climate change and increasing stress on water systems. There are large-scale models fully devoted to aspects of these systems, and many have a breadth and depth of coverage well beyond that of IFs. Yet in some cases, including the treatment of infrastructure, IFs has broken new ground.

What the discussion in this chapter did not do was direct attention to the consequences of resultant environmental change for broader human and social development. The next chapter turns to that.

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S., 2003a. Development and testing of the water GAP 2 global model of water use and availability. Hydrol. Sci. 48 (3), 317–337. https://dx.doi.org/10.1623/hysj.48.3.317.45290.

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S., 2003b. Global estimates of water withdrawals and availability under current and 'business-as-usual' conditions. Hydrol. Sci. 48 (3), 339–348. https://dx.doi.org/10.1623/hysj.48.3.339.45278.

Alexandratos, N., Bruinsma, J., 2012. World Agriculture Towards 2030/2050: The 2012 Revision. ESAWorking Paper 12-03. Rome, Italy, Agricultural Development Economics Division, Food and Agriculture Organization. http://www.fao.org/docrep/016/ap106e/ap106e.pdf.

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., et al., 2017. Shared socio-economic pathways of the energy sector – quantifying the narratives. Glob. Environ. Chang. 42 (January), 316–330. https://dx.doi.org/10.1016/j.gloenvcha.2016.07.006.

Beck, H.E., van Dijk, A.I.J.M., Miralles, D.G., de Jeu, R.A.M., Bruijnzeel, L.A. (Sampurno), McVicar, T.R., Schellekens, J., 2013. Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. Water Resour. Res. 49 (12), 7843–7863. https://dx.doi.org/10.1002/2013WR013918.

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., et al., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Chang. Biol. 13 (3), 679–706. https://dx.doi.org/10.1111/j.1365-2486.2006.01305.x.

Calderón, C., Servén, L., 2010. Infrastructure and economic development in sub-saharan Africa. J. Afr. Econ. 19 (Supplement 1), i13–i87. https://dx.doi.org/10.1093/jae/ejp022.

Chen, C., Hagemann, S., Clark, D., Folwell, S., Gosling, S., Haddeland, I., et al., 2011. Projected Hydrological Changes in the 21st Century and Related Uncertainties Obtained from a Multi-Model Ensemble. EU WATCH Water and Global Change (WATCH) Project Technical Report no. 45. Project coordinated by Centre for Ecology and Hydrology, Oxfordshire, UK. http://www.eu-watch.org/media/default.aspx/emma/org/10826413/WATCH+Technical+Report+Number+45+Projected+hydrological+changes+in+the+21st+century+and+related+uncertainties+obtained+from+a+multi-model+ensemble.pdf.

Cline, W.R., 2007. Global Warming and Agriculture: Impact Estimates by Country. Center for Global Development and Peterson Institute for International Economics, Washington, DC.

Darmstadter, J., Teitelbaum, P.D., Polach, J.G., 1971. Energy in the World Economy: A Statistical Review of Trends in Output, Trade, and Consumption Since 1925. Johns Hopkins Press, Baltimore, MD.

Davies, E.G.R., Kyle, P., Edmonds, J.A., 2013. An integrated assessment of global and regional water demands for electricity generation to 2095. Adv. Water Resour. 52 (February), 296–313. https://dx.doi.org/10.1016/j.advwatres.2012.11.020.

Davis, S.J., Cao, L., Caldeira, K., Hoffert, M.I., 2013. Rethinking wedges. Environ. Res. Lett. 8 (1), 1–8. https://dx.doi.org/10.1088/1748-9326/8/1/011001.

Devi, G.K., Ganasri, B.P., Dwarakish, G.S., 2015. A review on hydrological models. Aquat. Procedia 4, 1001–1007. https://dx.doi.org/10.1016/j.aqpro.2015.02.126.

Dietrich, J.P., Schmitz, C., Lotze-Campen, H., Popp, A., Müller, C., 2014. Forecasting technological change in agriculture – an endogenous implementation in a global land use model. Technol. Forecast. Soc. Chang. 81 (January), 236–249. https://dx.doi.org/10.1016/j.techfore.2013.02.003.

Energy Transitions Commission, 2017. Better Energy, Greater Prosperity: Achievable Pathways to Low-Carbon Energy Systems. Energy Transition Commission. Available from: http://www.energy-transitions.org/better-energy-greater-prosperity.

Evans, R.G., John Sadler, E., 2008. Methods and technologies to improve efficiency of water use. Water Resour. Res. 44 (7): W00EO4, 15 pages. https://doi.org/10.1029/2007WR006200.

Fader, M., Dieter, G., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W., Cramer, W., 2011. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. Hydrol. Earth Syst. Sci. 15 (5), 1641–1660. https://dx.doi.org/10.5194/hess-15-1641-2011.

Fay, M., 2001. Financing the Future: Infrastructure Needs in Latin America, 2000–05. WB Policy Research Working Paper no. 2545. World Bank, Washington, DC. https://dx.doi.org/10.1596/1813-9450-2545.

Fay, M., Yepes, T., 2003. Investing in Infrastructure: What Is Needed from 2000 to 2010? WB Policy Research Working Paper no. 3102. World Bank, Washington, DC. http://ideas.repec.org/p/wbk/wbrwps/3102.html.

Federal Institute for Geosciences and Natural Resources (BGR), 2016. Energy Study 2016: Reserves, Resources, and Availability of Energy Resources. Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany. https://www.bgr.bund.de/EN/Themen/Energie/Downloads/energiestudie_2016_en.pdf?__blob=publicationFile&v=2.

Flörke, M., Eisner, S., 2011. , The Development of Global Spatially Detailed Estimates of Sectoral Water Requirements, Past, Present and Future, including Discussion of the Main Uncertainties, Risks and Vulnerabilities of Human Water Demand. EU WATCH project Technical Report No. 46. Center for Environmental Systems Research, Kassel, Germany. http://www.eu-watch.org/media/default.aspx/emma/org/10730466/Technical+Report+46+Development+of+Spatially+detailed+global+estimates+of+20th+and+21st+Century+sectoral+water+requirements.pdf.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., Alcamo, J., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: a global simulation study. Glob. Environ. Chang. 23 (February), 144–156. https://dx.doi.org/10.1016/j.gloenvcha.2012.10.018.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., et al., 2017. The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century. Glob. Environ. Chang. 42 (January), 251–267. https://dx.doi.org/10.1016/j.gloenvcha.2016.06.004.

Global Energy Assessment Writing Team (GEA), 2012a. Global Energy Assessment: Toward a Sustainable Future. Full Report. Cambridge University Press and International Institute for Applied Systems Analysis, Cambridge, UK, and Laxenburg, Austria.

Global Energy Assessment Writing Team (GEA), 2012b. Global Energy Assessment: Toward a Sustainable Future - Key Findings, Summary for Policymakers, [and] Technical Documentation. Cambridge University Press and International Institute for Applied Systems Analysis, Cambridge, UK, and Laxenburg, Austria.

Gouel, C., Guimbard, H., 2017. Nutrition transition and the structure of global food demand. IFPRI Discussion Paper 01631. International Food Policy Research Institute, Washington, DC. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/131130.

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., et al., 2013a. A global water scarcity assessment under shared socio-economic pathways – part 1: water use. Hydrol. Earth Syst. Sci. 17 (7), 2375–2391. https://dx.doi.org/10.5194/hess-17-2375-2013.

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., et al., 2013b. A global water scarcity assessment under shared socio-economic pathways – part 2: water availability and scarcity. Hydrol. Earth Syst. Sci. 17 (7), 2393–2413. https://dx.doi.org/10.5194/hess-17-2393-2013.

Hartin, C.A., Patel, P., Schwarber, A., Link, R.P., Bond-Lamberty, B., 2015. A simple object-oriented and open-source model for scientific and policy analyses of the global climate system–hector v 1.0. Geosci. Model Dev. 8, 939–955. https://dx.doi.org/10.5194/gmd-8-939-2015.

Hedden, S., Hughes, B.B., Rothman, D.S., Markle, A.J., Maweni, J., Mayaki, I.A., 2016. The Elimination of Hunger and Food Insecurity on the African Continent by 2025 – Conditions for Success. The New Partnership for African Development Planning and Coordinating Agency (NEPAD) and the Frederick S. Pardee Center for International

Futures, Midrand, South Africa, and Denver, CO. http://www.nepad.org/resource/ending-hunger-africa-elimination-hunger-and-food-insecurity-african-2025-conditions-success.

Hubbert, M.K., 1956. Nuclear Energy and the Fossil Fuels. Paper Presented at the Spring Meeting of the American Petroleum Institute Southern District, San Antonio, Texas, March 7–9. http://www.hubbertpeak.com/hubbert/1956/1956.pdf.

Hughes, B.B., Irfan, M.T., Moyer, J.D., Rothman, D.S., Solórzano, J.R., 2011. Forecasting the Impacts of Environmental Constraints on Human Development. Human Development Research Paper 2011/08. United Nations Development Programme, New York, NY. http://hdr.undp.org/sites/default/files/hdrp_2011_08.pdf.

Hughes, G., Chinowsky, P., Strzepek, K., 2010. The Costs of Adapting to Climate Change for Infrastructure. Economics of Adaptation to Climate Change Discussion Paper no. 2. 2010. World Bank, Washington, DC. http://siteresources.worldbank.org/EXTCC/Resources/407863-1229101582229/DCCDP_2Infrastructure.pdf.

Intergovernmental Panel on Climate Change (IPCC), 2000. Emissions Scenarios: Summary for Policymakers. IPCC Working Group III Special Report, IPCC Secretariat, Geneva, Switzerland. https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf.

Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2014 Synthesis Report: Summary for Policymakers. IPCC Secretariat, Geneva, Switzerland. https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf.

International Energy Agency (IEA), 2015. World Energy Model Documentation: 2015 Version. International Energy Agency, Paris, France. http://www.worldenergyoutlook.org/media/weowebsite/2015/WEM_Documentation_WEO2015.pdf.

International Energy Agency (IEA), 2016. World Energy Outlook 2016. International Energy Agency, Paris, France.

International Energy Agency (IEA), 2018. World Energy Outlook 2018. International Energy Agency, Paris, France.

Jouzel, J., 2013. A brief history of ice core science over the last 50 years. Clim. Past 9 (6), 2525–2547. https://dx.doi.org/10.5194/cp-9-2525-2013.

Kim, S.H., Hejazi, M., Lu, L., Calvin, K., Clarke, L., Edmonds, J., et al., 2016. Balancing global water availability and use at basin scale in an integrated assessment model. Clim. Chang. 136 (2), 217–231. https://dx.doi.org/10.1007/s10584-016-1604-6.

Kohli, H.A., Basil, P., 2011. Requirements for infrastructure investment in latin america under alternate growth scenarios. Glob. J. Emerg. Mark. Econ. 3 (1), 59–110. https://dx.doi.org/10.1177/097491011000300103.

Kohli, H.A., Mukherjee, N., 2011. Potential costs to Asia of the middle income trap. Glob. J. Emerg. Mark. Econ. 3 (3), 291–311. https://dx.doi.org/10.1177/097491011100300303.

Krey, V., 2014. Global energy-climate scenarios and models: a review. WIREs Energy Environ. 3 (4), 363–383. https://dx.doi.org/10.1002/wene.98.

Kumar, S., 2013. The looming threat of water scarcity. Vital Signs Online, A Worldwatch Institute Publication. article, Available from: http://vitalsigns.worldwatch.org/vs-trend/looming-threat-water-scarcity.

Kypreos, S., Bahn, O., 2003. A MERGE model with endogenous technological progress. Environ. Model. Assess. 8 (3), 249–259. https://dx.doi.org/10.1023/A:1025551408939.

Lovins, A.B., 1985. Saving gigabucks with negawatts. Public Util. Fortnig. 115 (6), 19–26.

Luderer G., Kriegler E., Delsa L., Edelenbosch O., Emmerling J., Krey V., et al., 2016. Deep Decarbonisation towards 1.5°C -2°C Stabilisation. The ADVANCE Consortium, coordinated by the Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó., Taylor, R.G., 2012. Quantitative maps of groundwater resources in Africa. Environ. Res. Lett. 7(2)024009. https://dx.doi.org/10.1088/1748-9326/7/2/024009.

McCollum, D., 2012. The IIASA Energy-Multi Criteria Analysis Tool (ENE-MCA). User Manual. International Institute for Applied Systems Analysis, Laxenburg, Austria. https://core.ac.uk/download/pdf/129969426.pdf.

McKelvey, V.E., 1972. Mineral resource estimates and public policy. Am. Sci. 60 (1), 32–40. http://www.jstor.org.du.idm.oclc.org/stable/27842943.

McNeil, J.R., 1992. The Mountains of the Mediterranean World: An Environmental History. Cambridge University Press, Cambridge, UK.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC. http://www.millenniumassessment.org/documents/document.356.aspx.pdf.

Mulders, F.M.M., Hettelar, J.M.M., van Bergen, F., 2006. Assessment of the Global Fossil Fuel Reserves and Resources for TIMER. Report no. 2006-u-ROOO3/B. TNO Built Environment and Geosciences, Utrecht, the Netherlands.

Nelson, G.C., Valin, H., Sands, R.D., Havlik, P., Ahammad, H., Deryng, D., et al., 2014. Climate change effects on agriculture: economic responses to biophysical shocks. Proc. Natl. Acad. Sci. 111 (9), 3274–3279. https://dx.doi.org/10.1073/pnas.1222465110.

O'Neill, B.C., Dalton, M., Fuchs, R., Jiang, L., Pachauri, S., Zigova, K., 2010. Global demographic trends and future carbon emissions. PNAS 107 (31), 17521–17526. https://dx.doi.org/10.1073/pnas.1004581107.

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., et al., 2016. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci. Model Dev. 9 (9), 3461–3482. https://dx.doi.org/10.5194/gmd-9-3461-2016.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Dale S. Rothman, et al., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42 (January), 169–180. https://dx.doi.org/10.1016/j.gloenvcha.2015.01.004.

Olson, M., 1965. The Logic of Collective Action. Harvard University Press, Cambridge, MA.

Organisation for Economic Co-operation and Development (OECD), 2012. OECD Environmental Outlook to 2050: The Consequences of Inaction. OECD, Paris, France. https://dx.doi.org/10.1787/9789264122246-en.

Pacala, S.W., Socolow, R., 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305 (5686), 968–972. https://dx.doi.org/10.1126/science.1100103.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob. Environ. Chang. 14 (1), 53–67. https://dx.doi.org/10.1016/j.gloenvcha.2003.10.008.

Phillips, N.A., 1956. The general circulation of the atmosphere: a numerical experiment. Q. J. R. Meteorol. Soc. 82 (352), 123–164. https://dx.doi.org/10.1002/qj.49708235202.

Qiang, C.Z.-W., Rossotto, C.M., Kimura, K., 2009. Economic impacts of broadband. In: World Bank, (Ed.), 2009 Information and Communications for Development: Extending Reach and Increasing Impact. World Bank, Washington, DC, pp. 35–50.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42 (January), 153–168. https://dx.doi.org/10.1016/j.gloenvcha.2016.05.009.

Robinson, S., Mason-D'Croz, D., Islam, S., Sulser, T.B., Robertson, R., Zhu, T., et al., 2015. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description for Version 3. IFPRI Discussion Paper no. 1483. International Food Policy Research Institute, Washington, DC. https://dx.doi.org/10.13140/RG.2.1.4865.1607.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., et al., 2016. Paris agreement climate proposals need a boost to keep warming well below 2°C. Nature 534 (7609), 631–639. https://dx.doi.org/10.1038/nature18307.

Rogner, H.-H., 1997. An assessment of world hydrocarbon resources. Annu. Rev. Energy Environ. 22 (1), 217–262. https://dx.doi.org/10.1146/annurev.energy.22.1.217.

Rogner, H.-H., Aguilera, R.F., Archer, C.L., Ruggero, B., Bhattacharya, S.C., Maurice B. Dusseault, et al., 2012. Energy resources and potentials. In: Johansson, T.B., Patwardhan, A., Nakicenovic, N., Gomez-Echeverri, L. (Eds.), Global Energy Assessment: Toward a Sustainable Future. Cambridge University Press, Cambridge, UK, pp. 425–512. www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter7_resources_hires.pdf.

Rosegrant, M.W., IMPACT Development Team, 2012. International Model for Policy Analysis of Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute, Washington, DC. http://technicalconsortium.org/wp-content/uploads/2014/05/International-model-for-policy-analysis.pdf.

Rosegrant, M.W., Agcaoili-Sombilla, M., Perez, N.D., 1995. Global Food Projections to 2020: Implications for Investment. Food, Agriculture, and the Environment Discussion Paper 5. International Food Policy Research Institute, Washington, DC. http://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/125553/filename/125584.pdf.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., et al., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. PNAS 111 (9), 3268–3273. https://dx.doi.org/10.1073/pnas.1222463110.

Rothman, D.S., Irfan, M.T., 2013. IFs Infrastructure Model Documentation. Working Paper 2013.07.22. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://pardee.du.edu/sites/default/files/Infrastructure%20Documentation%20v12%20-%20clean.pdf.

Rothman, D.S., Agard, J., Alcamo, J., 2007. The future today. In: United Nations Environment Programme, Global Environment Outlook 4 (GEO 4): Outlook for Development. United Nations Environment Programme, Nairobi, Kenya, pp. 397–456.

Rothman, D.S., Irfan, M.T., Margolese-Malin, E., Hughes, B.B., Moyer, J.D., 2014. Building Global Infrastructure. Patterns of Potential Human Progress Series, vol. 4. Paradigm Publishers and Oxford University Press, Boulder, CO, and New Delhi, India.

Shiklomanov, I.A., 2000. Appraisal and assessment of world water resources. Water Int. 25 (1), 11–32. https://dx.doi.org/10.1080/02508060008686794.

Smith, M., 1992. CROPWAT: A Computer Program for Irrigation Planning and Management. Food and Agriculture Organization of the United Nations, Rome, Italy.

Stehfest, E., van den Berg, M., Woltjer, G., Msangi, S., Westhoek, H., 2013. Options to reduce the environmental effects of livestock production–comparison of two economic models. Agric. Syst. 114 (January), 38–53. https://dx.doi.org/10.1016/j.agsy.2012.07.002.

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L. (Eds.), 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications. PBL Report no. 735. PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands. http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2014-integrated%20assessment%20of%20global%20environmental%20change%20with%20image30_735.pdf.

Stevens, B., Schieb, P.-A., Andrieu, M., 2006. Across-sectoral perspective on the development of global infrastructures to 2030. In: Organisation for Economic Co-operation and Development (OECD), (Ed.), Infrastructure to 2030: Telecom, Land Transport, Water and Electricity, vol. 1. OECD, Paris, France, pp. 13–49. https://dx.doi.org/10.1787/9789264023994-en.

Sverdrup, H.U., Vala Ragnarsdóttir, K., 2014. Natural resources in a planetary perspective. Geochem. Perspect. 3 (2), 129–336. https://dx.doi.org/10.7185/geochempersp.3.2.

United Nations Convention to Combat Desertification (UNCCD), 2017. Global Land Outlook, first ed. Secretariat of the United Nations Convention to Combat Desertification, Bonn, Germany.

United Nations Environment Programme (UNEP), 2001. GLOBIO: Global Methodology for Mapping Human Impacts on the Biosphere. UNEP/DEWA/TR.01-3. United Nations Environment Programme, Nairobi, Kenya.

United Nations Environment Programme (UNEP), 2017. The Emissions Gap Report 2017. United Nations Environment Programme, Nairobi, Kenya. https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf.

United States Government Accountability Office (U.S. GAO), 2007. Crude Oil: Uncertainty About Future Oil Supply Makes it Important to Develop a Strategy for Addressing a Peak and Decline in Oil Production. GAO-07-283. Washington, DC, Government Accountability Office. http://www.gao.gov/new.items/d07283.pdf.

van Vuuren, D.P., Kok, M., 2012. Roads from Rio+20: Pathways to Achieve Global Sustainability Goals by 2050. Full Report. PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands. http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2012-roads-from-rio-pathways-to-achieve-global-sustainability-goals-by-2050.pdf.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al., 2011a. The representative concentration pathways: an overview. Clim. Chang. 109 (1–2), 5–31. https://dx.doi.org/10.1007/s10584-011-0148-z.

van Vuuren, D.P., Lowe, J., Stehfest, E., Gohar, L., Hof, A.F., Hope, C., et al., 2011b. How well do integrated assessment models simulate climate change? Clim. Chang. 104 (2), 255–285. https://dx.doi.org/10.1007/s10584-009-9764-2.

van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., van den Berg, M., Harmsen, M., et al., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob. Environ. Chang. 42 (January), 237–250. https://dx.doi.org/10.1016/j.gloenvcha.2016.05.008.

von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., et al., 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison. Agric. Econ. 45 (1), 3–20. https://dx.doi.org/10.1111/agec.12086.

Wada, Y., 2016. Modeling groundwater depletion at regional and global scales: present state and future prospects. Surv. Geophys. 37 (2), 419–451. https://dx.doi.org/10.1007/s10712-015-9347-x.

Wada, Y., Bierkens, M.F.P., 2014. Sustainability of global water use: past reconstruction and future projections. Environ. Res. Lett. 9(10):104003. https://dx.doi.org/10.1088/1748-9326/9/10/104003.

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., Bierkens, M.F.P., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37(20):L20402. https://dx.doi.org/10.1029/2010GL044571.

Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., et al., 2013. Multimodel projections and uncertainties of irrigation water demand under climate change. Geophys. Res. Lett. 40 (17), 4626–4632. https://dx.doi.org/10.1002/grl.50686.

Wada, Y., Wisser, D., Bierkens, M.F.P., 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dynam. 5 (1), 15–40. https://dx.doi.org/10.5194/esd-5-15-2014.

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., et al., 2016. Modeling global water use for the 21st century: the water futures and solutions (WFaS) initiative and its approaches. Geosci. Model Dev. 9 (1), 175–222. https://dx.doi.org/10.5194/gmd-9-175-2016.

Wigley, T.M.L., 2008. MAGICC/SCENGEN 5.3: User Manual (Version 2). National Center for Atmospheric Research, Boulder, CO. http://www.cgd.ucar.edu/cas/wigley/magicc/UserMan5.3.v2.pdf.

CHAPTER

8

Feedbacks and Disruption: Sources of Uncertainty

Fig. 3.1 identified the systems of interest to integrated assessment modeling (and world modeling before it), and Fig. 4.1 showed the models that make up the integrated International Futures (IFs) system. This volume has proceeded to discuss those systems and models by issue area, organized generally in the domains of human capabilities, social change, and sustainable development. We have seen that, as uncertain as many elements of modeling are within the various issue areas of this volume, understanding and representing the complex and bidirectional linkages across areas can be even more challenging. That was true, for instance, in the discussions of Chapter 6 around economic productivity and government spending patterns, two areas where threads from many issue domains converge.

In discussion to this point I have dealt only very selectively with one very important set of those complex cross-issue linkages, namely feedbacks from changes we help create in biophysical systems, like climate and water, to human systems, including the economy. Those linkages and feedbacks are the major focus of this chapter.

The volume has frequently pointed to the challenge for global models of addressing major forces of disruption. A primary source of disruption across all issue areas, but one that I have not addressed in much detail, is technology. The unfolding of technological change across the rest of this century is definitely one of the key sources of uncertainty in thinking about global and more-local futures. It is the second focus of the chapter.

The very fact that these two topics remain for us to consider suggests the extent of difficulty and uncertainty associated with them. Addressing them here will serve in part as a bridge to the next chapter, which closes the volume with a more general consideration of uncertainty and treatment of it by model builders and users.

8.1 BIOPHYSICAL SYSTEM LINKAGES BACK TO HUMAN ONES: THE IMPACT OF CHANGE

Chapter 7 emphasized our dependence as a species on our biophysical environment, from the air we breathe to the food we eat and the comforts we enjoy. In that chapter's modeling of

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agriculture, energy, and infrastructure systems and their environmental impacts, representation of underlying patterns of growth in human numbers and economic activity was essential, especially in determining demand. But what about feedbacks from those environmental impacts to human development and socioeconomic systems? Many integrated assessment models (IAMs) can provide important insights on possible nutrition levels and access to energy, as well as some information about health (affected by warming and nutrition). For instance, within the IMAGE suite, the Global Integrated Sustainability MOdel (GISMO) represents selected human development impacts of climate change, including malarial and other environmental system-related mortality.

Yet few IAMs link back environmental damage to economic growth except to that of the agriculture and energy sectors, and almost all take demographic patterns exogenously. I am unaware of any that project impacts on extreme poverty levels, the advance of education, or quality of governance (including security, capacity, or inclusion dimensions). Fig. 8.1 suggests some of the many possible feedback linkages and dynamics.

To some extent, those who model environmental change have had their hands full and have needed to take for granted that the broader human and social impacts of such change

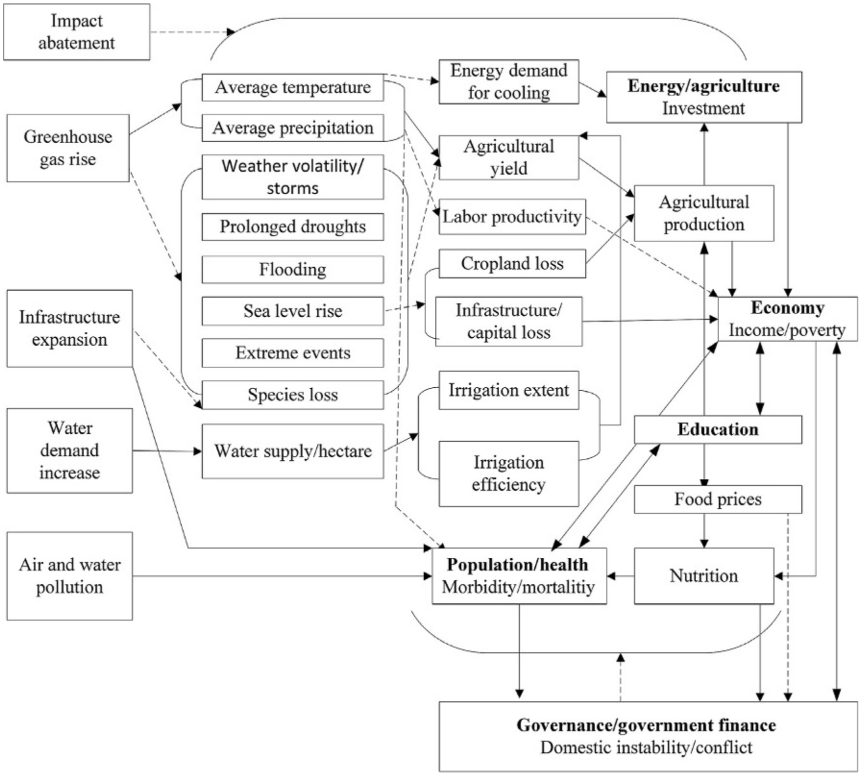

FIG. 8.1 **Illustrative environment system impacts on human and social systems.**
Note: Solid lines show linkages in IFs, dashed lines are not in IFs as of this writing, bold text indicates larger system/model in IFs. Figure does not show the many linkages back to environmental change. Source: Author.

would be very substantial (and very difficult to formalize). They have recognized, however, the importance of attention, at least in scenarios, to the concepts of vulnerability, risk, mitigation, and adaptation. For instance, the Shared Socioeconomic Pathway (SSP) scenarios (see Section 3.3.2.1) are framed by socioeconomic challenges for mitigation and adaptation, and some analysis with models has focused on concepts such as vulnerability and risk (e.g., see Birkmann et al., 2013). Clearly, however, for the purposes both of understanding larger global dynamics and of supporting policy analysis (which requires insight concerning costs and benefits, trade-offs and synergies), global modelers really do need to understand the broad range of the impacts of environmental change. Elaboration of the Sustainable Development Goals framework has reinforced need for attention across developmental issue groupings, and qualitative analyses of human and social development have long recognized the potentially disruptive impacts of changes in biophysical systems. Even so, as Verburg et al. (2016) pointed out, there is a paucity of systems with bidirectionally integrated socioecological components. Some IAMs and some specialized IAM projects, including CD-LINKS and The World in 2050, are increasingly moving to pick up that challenge.

8.1.1 Uncertain Knowledge About Environmental Impacts

While inclusion in IAMs may lag, there is no lack of scientific and research attention to environmental impacts on human systems, including that of climate change, to which I give special attention in this discussion. In the Intergovernmental Panel on Climate Change (IPCC) process, Working Group II focuses on the vulnerability of socioeconomic as well as natural systems to climate change, including positive and negative impacts and options for adaptation. Although the working group draws on insights from IAMs as possible, it reaches out to a very wide range of more specialized scientific studies. In the fifth assessment, Working Group II's central report ran more than 1800 pages and cited many hundred scientific studies (IPCC, 2014). That report therefore provides tremendous fodder for modeling of impacts, as will the sixth in 2022.

Unfortunately, the level of uncertainty is high on many of those impacts, perhaps especially the socioeconomic ones, complicating their representation in models. For example, with respect to general economic impact, the Technical Summary of Working Group II in that fifth assessment indicated that:

> Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors. With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income … Losses are more likely than not to be greater, rather than smaller, than this range (limited evidence, high agreement). Additionally, there are large differences between and within countries … [and] few quantitative estimates have been completed for additional warming around 3°C or above. (Field et al., 2014, p. 71)

Chapter 12 in the report indicated that estimates of the economic damages per ton of carbon emitted vary by two orders of magnitude (from a few dollars to several hundred) across studies (Arent and Tol, 2014, pp. 692–693). The differences heavily reflect variations in the discount rate applied to future impacts, a topic discussed further later in the chapter.

With respect to the issue of poverty, the review of it in Chapter 13 of the Working Group II report concluded that:

> Poverty dynamics are not sufficiently accounted for in current climate change research… . Many of these dynamics remain hidden, incompletely captured in poverty statistics and disaster and development discourses. Key assumptions in many economic models (e.g., constant within-country distribution of per capita income over time, linear relationship between economic growth and poverty headcounts) are ill suited to capture local and subnational poverty dynamics, confounding projections of future poverty levels. (Olsson et al., 2014, p. 818)

Throughout the report, references to individual studies sometimes provided specific estimates of climate change impact, but across each literature—whether it be on economic growth or poverty as discussed earlier, or on health, nutrition, or human security (including conflict)—the conclusions most often emphasized that uncertainty is very great. One reason for high uncertainty is again the complexity of dynamic linkages among many issue areas. The discussion here will draw in part on detailed topical studies, but the focus is, of course, on modeling of climate change impact.

8.1.2 Modeling Impacts From Environmental Change

Section 3.2.2 identified three models that are especially well known for their attention to the damage of climate change in the context of analysis of the social cost of carbon: Dynamic Integrated model of Climate and the Economy (DICE) or the regional version (RICE), climate Framework for Uncertainty, Negotiation, and Distribution (FUND), and Policy Analysis of the Greenhouse Effect (PAGE). A fourth model, Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) has many of the same features, but has been less widely used in comparative analyses. The models attempt to represent the full economic impact of climate change, including the monetized value of some impacts not captured in GDP. Consistent with the findings of the IPCC reports, one relatively striking outcome of analysis with these models is the somewhat modest economic impact that they collectively project from climate change across the century.

An extensive analysis by an Organisation for Economic Co-operation and Development report on the economic impact of climate change (OECD, 2015) used both a version of DICE and the OECD's own ENV-Linkages model. It concluded that should temperatures rise 4°C by century end, the negative global economic impact would range from 2% to 10% of GDP, with particular severity in Africa and Asia. (OECD, 2015, p. 3).[1]

In a more recent analysis with DICE, FUND, and PAGE, Rose et al. (2017, Figure 3) found that across emission scenarios producing atmospheric concentrations of carbon dioxide in 2100 ranging from just below 500 to 1000 ppm, the annual economic impact at end of century varied from very slightly positive (for instance, from warming leading to improvement of agriculture at high latitudes) to negative costs just over 4% of GDP. Results from FUND suggested the least impact. (Analysis with parameter changes showed uncertainty to be fairly

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[1] In another study, the OECD (2016) found that outdoor air pollution in 2060 could cost 1% of global GDP and 3% in China.

modest for FUND and very great for PAGE.) The Rose, Diaz, and Blanford work was part of a very extensive US government-commissioned analysis of the social cost of carbon by the National Academies of Sciences, Engineering, and Medicine (2017), which used the three models, compared them extensively, and provided detailed recommendations for pushing ahead such analytical effort.

The projected negative economic impacts from these models is obviously very important and could be much greater in some locations. However, when thinking about long-term human futures, we can also put them in the context of more than a six-fold increase in global GDP over that period (more than a quadrupling in per capita terms) anticipated in SSP2 scenario implementations and the IFs Base Case between 2015 and 2100.

Key questions become how the models work, how the estimates of damage are made, and how great the uncertainty and possibly unknown risk might be. There are two general approaches to introducing the linkage from climate change, and implicitly from related environmental changes including water scarcity and loss of biodiversity, back to the economy and to broader human and social systems. Tol (2009) designated them as *enumerative* and *statistical* methods.[2] In fact, however, the enumerative approach is often not greatly different from the statistical approach except in level of aggregation of the damage categories.

The former (illustrated by Fig. 8.1) sometimes elaborates structurally specific or process-based physical impacts. A good example is from the agriculture sector, where changes in temperature and precipitation affect yield and therefore agricultural production and its value within the GDP. The enumerative approach as used by Tol in FUND statistically summarizes knowledge about such impacts across many process-based analyses (see also the National Academies of Sciences, Engineering, and Medicine, 2017, p. 139). IAMs and issue-specific models can contribute to such process-based knowledge. Many enumerated impacts tend, however, to be estimated statistically without process-elaborating foundation. The enumerative approach then aggregates all such impacts and sometimes adds a more general representation for possible omissions. Tol and his collaborators have built FUND heavily in that manner.

The second approach is more aggregate and purely statistical, and looks across space and time, within and between countries, at the relationship between climate variables and prices, expenditures, and general welfare (possibly sectoral but often for the total economy) without mapping specific physical paths. Among others, Mendelsohn et al. (2000) have undertaken much such analysis, while Nordhaus and collaborators (Nordhaus, 2016; Nordhaus and Sztorc, 2013) have drawn upon results within the DICE/RICE model family.

Across approaches, the ultimate specification within models of impacts from environmental change utilizes damage functions. Damage functions generally link future temperature change to specific impacts or to the total economy using quite simple quadratic or power functions, so that impact grows exponentially with temperature variation from a base-year level (usually pre-industrial or 1990) or from an exogenously specified optimum level.

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[2] A recent team effort through the collaborative Climate Impact Lab used a third approach—automated econometric analysis of big data coupled with localized climate projections (see http://www.impactlab.org/our-approach/).

8.1.2.1 Challenges: Causal Representations (Especially of Extreme Events)

The challenges that various approaches face fall roughly into two categories: (1) their causal representation and (2) their temporal treatment.

With respect to *causal representation*, one key issue is whether the models are focused only or largely on the impacts of average change in temperature and precipitation—many models, including IFs, represent the feedbacks of these to agriculture. Or might they also capture increased volatility and frequency of extreme events, and possibly even somehow represent unknown effects that might include passing of major tipping events that change basic dynamics of some global systems?

Tipping points are by definition reached when human or biophysical systems are pushed "past critical states into qualitatively different modes of operation" (Lenton et al., 2008, p. 1). We should recognize that the distinction between, and the interactions of, extreme events and tipping points are not always clear. Extreme events like exceptionally high temperatures and prolonged droughts can occur, even with greater frequency, in systems that are operating much as they long have. They might also lead, however, to tipping of systems, such as if melting of the ice sheet of Greenland contributes to the disruption of ocean circulation patterns. And not all system tipping requires extreme events. A relatively modest but prolonged rise of temperature could generate that ice sheet melting and broader system change. Regardless of the terminology, extreme events and tipping points are obviously of great interest to us, and modelers struggle to represent them.

Tol's (2009) review of 13 model-based estimates of percentage of annual GDP lost in 2100 as a result of a doubling of atmospheric carbon, with associated global warming of about 3°C, suggested a global GDP loss of about 2%–3%, and from 2 to 10 times that amount in Africa. Because of the omission of unknown effects in the studies, however, he cautioned that the risk is significant on the upward side. Specifically, Tol (2009) identified some of the smaller, middle-sized, and larger uncertainties; in the last category he noted "extreme climate scenarios, the very long-term, biodiversity loss, the possible effects of climate change on economic development, and even political violence" (Tol, 2009, p. 44).

Some statistical approaches attempt in general terms to address such changing risk and the fact that almost all cost–benefit analysis assumes the normal thin tail of extreme events. Weitzman (2009) argued for use of a fat-tailed probability density function that would very substantially raise the likelihood of extreme events, including higher than expected temperature rise. Hansen et al. (2012) took a somewhat different approach and explored the historical change of extreme warm weather events, finding about a 10-fold increase over 30 years. While scientists have been very cautious about associating specific extreme weather events with global warming, they do track their frequency and character (European Academies Science Advisory Council, 2018).[3]

Those in the global modeling community recognize that some environmental impacts of human activity could lead to tipping points that could fundamentally alter behavior of biophysical systems and not only stop but actually reverse long-term trends of human progress.

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[3] Analysis in a special issue of the *Bulletin of the American Meteorological Society*, released in December 2017, explored three such events, including a high-temperature area of the Pacific Ocean during 2013–2016 nicknamed the "Blob." Reported by Carolyn Gramling, "Extreme Weather Linked to Humans," *Science News*, January 20, 2018, page 6.

They recognize also that model structures and projections very rarely represent such dynamics and that most attempts to do so fall short.[4] The earliest world modeling, especially the World3 model used in *The Limits to Growth* (Meadows et al., 1972), forecast rather stylized (and thus heavily criticized) catastrophic tipping and collapse in global systems in virtually all scenarios, driven by combinations of pressure on resource bases such as food or raw materials and by deterioration in environmental quality.[5] Some contemporary studies of global carrying capacity or planetary boundaries (e.g., Rockström et al., 2009) using tools such as ecological footprint analysis (see Rees and Wackernagel, 2013) suggest once again that we may well have passed the points at which highly disruptive problems are inevitable. Again however, IAM developers, emphasizing the importance of strong scientific basis, have almost always stopped short of building into their systems and endogenously representing the potential for, and impacts of, rapidly disruptive and possibly catastrophic consequences of environmental change.

8.1.2.2 Challenges: Temporal Considerations

Moving from challenges around causality of extreme events to those involving temporal dynamics and horizon, there are three interrelated challenges for both enumerative and statistical models: (1) the treatment of impacts as temporally specific or cumulative across time, (2) the appropriate horizon, and (3) how to think about the costs of damages far in the future relative to the costs of near-term interventions to mitigate them.

One issue that representations of climate impact in dynamic models must address is *the extent to which damage to the economy is for discrete time periods and the extent to which damage in any given year has implications for future years* thus compounding the impact across time. In modeling it is simple to represent damage with a multiplier on the production function affecting each period's GDP individually, and Nordhaus (2016) has taken this approach with DICE. Economic damage in a single period can, however, have a longer-term effect by lowering investment and therefore capital stock and knowledge in the longer term (although it can also be argued that such damage often mobilizes unused resources, an element of adaptation, thereby somewhat offsetting that affect). Elaborating the argument of cumulative and compounding impact, Dietz and Stern (2015, pp. 579–580) argued that climate-related economic damage will directly affect and reduce the stock of existing capital (e.g., direct damage to it or abandonment in instances such as sea level rise) and even associated total factor productivity (TFP). Use of a model like DICE or FUND with the addition of capital and productivity stock damage to that of annual production (a flow) can considerably increase the assessment of potential climate change cost at end of century to as much as 20% of GDP (Stern, 2007, using PAGE02). OECD (2015, pp. 81–84) also addressed this issue directly. In analysis using a version of the DICE model, directing 30% of annual damage to TFP and

[4] An exception is the representation in PAGE of economic consequences of discontinuous impacts of temperature change, such as the melting of the Greenland ice sheet (Hope, 2011, p. 8 in unpaginated document).

[5] Urdal (2005) reviewed the neoMalthusian literature linking population growth and associated environmental degradation to armed conflict. He found in a large-N empirical analysis across 50 years that there was no clear relationship between population growth rates and pressure on cropland and country-specific conflict. In decade-by-decade analyses, he found such a relationship only in the 1970s at the peak of population growth rates in developing countries and the explosion of limits-focused literature.

the rest to annual GDP increased the end of century annual reduction in GDP relative to a no-impact baseline to about 11%.

With respect to time horizons, most analyses stop at 2100, but atmospheric carbon increases will persist much longer. It is for this reason that analysis with FUND can extend through 3000 and that with PAGE through 2200. A central purpose of these models and DICE is to determine the social cost of greenhouse gas emissions, usually conceptualized as the long-term cumulative cost per ton of current carbon dioxide equivalent emission.

In computing those cumulative costs, *it is common to apply a discount rate to future costs*. This can be justified in part by anticipation of growing GDP per capita over time and therefore increased ease of absorbing such costs. It also can be more formally understood as the present value (also called discounted value or net present value) of future costs, related to the amount that would need be invested today to generate the value of those future costs in constant currency terms; the interest or other return expected and accumulated on the investment over time reduces the amount needed to meet the value of those future costs. It is common to use a discount rate for costs of future harm near 3% annually and as high as 5% (Stanton et al., 2008, pp. 12–13), somewhat in line with expected real return to capital. A 3% rate leads to valuation of each unit of cost at the end of the century at only about one twentieth of possible mitigation expenditures at the beginning of it and at negligible values when looking even further into the future. Stern (2007) discounted the value of costs for future generations by as little as 0.1% annually, however, arguing for intergenerational equity. Doing so led to much higher valuations of the cost of current emissions. That minimal discounting drew widespread criticism within the cost-benefit analysis field. Nordhaus (2016, p. 16) noted his use of 4.5%.

8.1.2.3 Enumerative Analysis: Illustrative Elements

Enumerative analysis directs us to a complex web of causal pathways like that of Fig. 8.1 but even more complex, as Carleton and Hsiang (2016) demonstrated in their survey of the range of possible social and economic impacts of climate. Ultimately, models using the enumerative approach must not only include multiple variables but also must aggregate the costs across paths, an issue to which discussion will return.

As discussed also in Section 7.4, a large number of studies and models have considered the impact of climate change on other biophysical systems, including water and the atmosphere, with much attention to specific biomes, forests, and fisheries.[6] At the interface of such biophysical systems and human activity, the climate's impact on agricultural yield has drawn particular attention. We know, however, that CO_2 fertilization[7] would at least partially offset the negative impact of warming on production and prices. Further, higher prices would encourage adaptation, including genetic improvement.

In analysis that considered a 4.4°C increase by the 2080s, Cline (2007, pp. 95–96) used fairly simple impact models to estimate a 15.9% decrease in global agricultural potential (3.2% after

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[6] The Inter-Sectoral Impact Model Intercomparison Project hosts a database that identifies and describes an extensive list of impact models at https://www.isimip.org/impactmodels/.

[7] CO_2 fertilization can, of course, be limited by the availability of other nutrients and water, and food responsive to it may be less nutritious.

factoring back in offsetting carbon fertilization benefits). The greatest losses would be in developing countries and especially Africa, where the projected decrease would be 27.5% without carbon fertilization or 16.6% with it. More recently, Zhao et al. (2017, p. 9326) summarized results from the use of multiple analytical methods, including drawing upon seven gridded crop models, and concluded: "Without CO_2 fertilization, effective adaptation, and genetic improvement, each degree-Celsius increase in global mean temperatures would, on average, reduce global yields of wheat by 6.0 percent, rice by 3.0 percent, maize by 7.0 percent, and soybeans by 3.1 percent." Again, greatest impact was on developing countries. Were the temperature to rise as in Cline's analysis, the Zhao et al. study indicated yield changes comparable to Cline's calculations.

In an intercomparison study looking across 10 economic models from the Agricultural Model Intercomparison and Improvement Project, von Lampe et al. (2014) found that a Representative Concentration Pathway (RCP) 8.5 scenario would raise global crop prices in 2050 between 2% and 79% relative to no climate change. Although many projections were in the 10%–20% range, the RCP8.5 scenario produced a very broad range of uncertainty.

Moving beyond the impact of climate change on agricultural yields (and therefore food prices) to impact on other socioeconomic systems is even more difficult and less common (Verburg et al., 2016). However, there are some pioneering efforts. One possible causal path is to sociopolitical instability, and even conflict, as a result of higher food prices and their associated impact on nutrition, especially in developing countries where agriculture is a larger share of the economy and nutrition levels are low. For instance, using aggregate data analysis, Bellemare (2015, p. 17) found that between 1990 and 2011 a "one-point increase in the Food and Agriculture Organization's food price index caused a 0.6 percent increase in the likelihood that a food riot will take place in Africa." Using the UNCTAD food price index and the general protests and riots variable from PRIO's Urban Social Disturbance in Africa and Asia database[8] to explore the same question, Hendrix and Haggard (2015, pp. 147–150) found that a one standard deviation increase in the food price index was associated between 1960 and 2010 with a 13% increase in protests and riots, and that democracies were especially vulnerable. On this topic, see also Fjelde (2015) and Koren and Bagozzi (2016).

While such studies have begun to create the basis for linking climate change through paths like agricultural yields and prices on to conflict and broader social and human development, process-focused analysis of the longer causal chain is at an early stage. Burke et al. (2009) used African climate and conflict data from 1981 to 2002 to estimate statistically a direct model of the relationship of temperature change with civil war. Then, looking forward, they used climate projections from 20 general circulation models with a range of temperature increase of 0.7–1.6°C for the African continent through 2030. Burke et al. (2009, p. 20670) concluded that climate change could raise conflict incidence in Africa by 54% in 2030, causing 353,000 battle deaths. Although there could be multiple paths between climate change and conflict, they pointed especially to food insecurity. More generally, Schleussner et al. (2016, p. 9216) found that across 50 countries from 1980 to 2010 "… about 23% of conflict outbreaks in ethnically highly fractionalized countries robustly coincide with climatic calamities."

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[8] UNCTAD is the United Nations Conference on Trade and Development and PRIO is the Peace Research Institute Oslo.

In addition to agriculture, another economic sector on which climate change will have a major impact is energy. Direct impacts include the positive feedback loop linking warming to increased energy demand for cooling. With the FUND model, Anthoff and Tol (2014a,b) identified increased costs of cooling as the major single economic cost of warming. More indirect impacts could include the costs of additional energy investment and/or of stranding existing and no longer economically viable capital stocks in the face of mitigation efforts.

Understanding the larger economic impact of sectoral dynamics such as those in agriculture and energy (or also in health care) poses great challenges. Potential for, and costs of, adaptation are complicated to represent in any model, including general equilibrium systems. Consider the balance between two realities. First, agriculture and energy are only about 6% and 3% of global GDP, respectively, and require roughly similar respective shares of global investment (a fact that raises some doubts about analyses that find increased cooling costs to have a potentially large impact on global GDP).[9] Although not true in places like sub-Saharan Africa, where the shares of investment are closer to 18% and 8%, this would seem to make it relatively easy for those sectors to adapt to stresses placed upon them, whether economic (such as resource limitation), technological, or environmental. The second reality, however, is that energy and agriculture are the rabbits in the elephant and rabbit economic stew. Although seemingly small shares of the economy, they are essential inputs. It can be challenging for models to balance representations of shorter-term constraint from smaller, essential sectors with longer-term adaptability driven by the larger economy.

This discussion has only scratched the surface of the pathways of climate change impact. A similar chain of logic to that of climate change on agricultural yield, food prices, nutrition, and conflict could be elaborated empirically from increasing water stress, whether resulting from climate change or from increasing water demand independent of it. Again, there are major complications, not least being the issue of how to represent change in the efficiency of irrigation (the biggest use of water) in the face of constrained supplies, which governments may or may not allow to affect prices.

8.1.2.4 Enumerative Analysis: Putting the Pieces Together

Potential structural pathways from climate change (or water stress) to human wellbeing are many and complicated. The situation becomes even more complicated when we consider feedback loops. The impacts on agricultural yield and production affect economic growth and therefore variables such as poverty level and nutrition. Changes in nutrition affect health (including infant mortality), with further impact on productivity and growth as well as on life expectancy. Both income levels and infant mortality can affect domestic stability and conflict potential, with additional implications for economic performance. Such a positive feedback system linking weakness in human development and poorer economic performance could

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[9] Űrge-Vorsatz et al. (2015, p. 96) indicate that energy use in buildings constitutes about 32% of total global demand, and they suggest that cooling consumes no more than one-third of that or about 10% of global total demand. Heating is somewhat more.

exacerbate the impact of climate change. At the same time, however, the negative feedback loop linking rise of agricultural prices to agricultural adaptation could reduce one of the immediate impacts of climate change. If the difficulty of assessing the more extended implications of even a single area of climate change's direct impact was not already very substantial, consider the complexity of attempting to analyze the extended, interacting dynamics of multiple direct impacts. It is useful to consider two efforts to do so.

One model based on the enumerative approach is FUND. The model (Anthoff and Tol, 2014a; parameters in Anthoff and Tol, 2014b; see also Bonen et al., 2014) incorporates nine damage function categories, not only linking warming to agricultural production and energy consumption (focusing on space heating and cooling) but also to tropical storms and extratropical storms (in both cases with separate functions for physical damage and mortality), sea level rise (value of drylands and wetlands inundated), forestry and water resources (both treated completely in monetary values rather than physical ones), the ecosystem and its biodiversity, and human health (with specification of mortality and morbidity from cardiovascular and respiratory, diarrheal, and vector-borne diseases). FUND's regional economic valuations for mortality and morbidity are functions of GDP per capita, a contentious specification (because it treats poor people as less valuable than richer ones) that remains common in policy analysis. The earlier discussion of the difficulty even of identifying impacts of climate change on yield, much less on conflict, plus Tol's own forthright discussion (2009) of potentially missing impacts when using the approach, help us understand the great uncertainties associated with the enumerative approach. The specific formulations and parameters in FUND have also drawn criticism for being based on older studies (Bonen et al., 2014, p. 47). There remains, of course, real value in the effort to elaborate the variety of impacts, to identify the more extended costs of each, and to summarize even the approximate magnitude of costs across them, as analysis with FUND has done.

Another model system taking an enumerative approach is the World Bank's ENVISAGE platform (Roson and van der Mensbrugghe, 2012; van der Mensbrugghe, 2013). ENVISAGE specifies labor productivity as the variable most vulnerable to climate change, but considers seven impact areas, including agriculture productivity, sea level rise, tourism, and energy demand. In the aggregate, it indicates a reduction of global GDP by 4.6% in 2100 in a scenario with temperature increase of 4.8°C (Roson and van der Mensbrugghe, 2012, p. 285).

Partially offsetting the difficulties of enumerative efforts, analyses of selected impacts have improved over time. One example is that of sea level rise. Hinkel et al. (2014, pp. 3293–3294) used the Dynamic Interactive Vulnerability Assessment (DIVA) database and model plus several other tools across RCP scenarios of 2.6, 4.5, and 8.5 (with associated temperature and sea level rise) in interaction with the Shared Socioeconomic Pathway scenarios. Without additional coastal protection, they found damage costs in 2100 to be 0.3%–5% of GDP under RCP2.6 and 1.2%–9.3% of GDP under RCP8.5; with coastal protection the costs were two to three orders of magnitude lower, and like costs relative to expected global GDP in 2100 were not dramatic ($12–$71 billion in $2005). Other studies have also found that widespread protection (impact abatement) reduces costs significantly (Anthoff et al., 2010). The analysis of Hinkel et al. (2014) was global in scale, however, and some countries would be devastated. Further, although the study included storm-associated costs, it did not represent possible change in storm frequency or intensity. Even more, 2100 is far from the appropriate end of the horizon in thinking about ice melting and sea level rise.

In short, the enumerative approach is attractive because it helps us think through specific causal dynamics, but its complexity helps explain the use also of the aggregated statistical approach.

8.1.2.5 Aggregated Statistical Representation

In contrast to the enumerative approach is the highly aggregated approach Nordhaus implemented with DICE, with a single damage function for all costs as a percentage of GDP. Moreover, in his DICE-2016R model version, Nordhaus (2016, pp. 13–14) simplified the quadratic equation's impact of temperature change on GDP by setting the intercept and linear terms to zero and assigning a core parametric value of 0.236 to the squared term. This resulted in a century-end economic loss of 2.1% at 3°C ($0.236*3^2$). Uncertainty analysis led to an addition of 50%, but subsequent calibration of the parameter from 27 studies (Nordhaus and Moffat, 2017) provided an estimated value at 3°C temperature increase of 2.04% of income (±2.21).[10]

The PAGE09 model (Hope, 2011) has complexity and structure between that of FUND and DICE.[11] PAGE09 differentiates four economic and noneconomic damage categories for eight world regions differing in vulnerability, and represents them as polynomial functions that respond to temperature differences from "tolerable" levels (which, in turn, can change with adaptation). Calibration sets damage at 4% of GDP for 2.5°C temperature rise (Hope, 2011, Figure 1 discussion in unpaginated document).[12] The model also represents abatement costs.

The parameterization of the aggregated approach is an obvious challenge and tends to look to insights of enumerative analysis (for example, as DICE has drawn on FUND). However, there have been a number of extensive statistical analyses of the relationship between historical temperature change and change in GDP or GDP per capita, and they have tended to identify considerably larger economic impact than those from enumerative analysis. For instance, Burke et al. (2018) analyzed the relationship for 165 countries from 1960 to 2010 with methods controlling for other time variant and time invariant factors (focusing on changes across time within countries rather than cross-national variation), and found that 2.5–3°C increase by 2100 could reduce global GDP per capita by 15%–25%, and that 4°C could cause reductions of more than 40%, about an order of magnitude greater than the results from the models discussed previously. See also related studies conducted by the Climate Impact Lab, a consortium of researchers who bring multiple methods to bear in estimating the costs of climate change and who find higher costs than represented in the major models of carbon's social costs.[13]

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[10] Although the DICE-2016R forecast for temperature change in 2100 is a fairly high 4°C, Nordhaus (2016, p. 7, 28) emphasized that this model version increased the annual rate of decarbonization to −1.5% because of acceleration in the 2000–2015 period.

[11] PAGE is less fully documented than FUND and DICE (Bonen et al., 2014, p. 43).

[12] Rose et al. (2017, see Figure 3) suggest that PAGE produces only 4% damage even at 4°C.

[13] The Climate Impact Lab is a consortium of researchers from the University of California Berkeley, The Energy Policy Institute at the University of Chicago, the Rhodium Group, and Rutgers University. See http://www.impactlab.org; http://www.impactlab.org/our-approach/.

Stepping back from a look at the enumerative and statistical modeling of environmental impacts it is important to reiterate both the importance of the effort and the continued analytical uncertainties that the IPCC process has recognized in each of its assessment rounds. In general, we know that there are major "known and unknown unknowns" in contemporary efforts to analyze the impacts of environmental change. Analysts therefore almost invariably use scenarios in any attempt to address them. The next chapter will discuss such efforts.

8.1.3 Modeling Environmental Impacts in IFs

Specifically elaborated (or enumerated) environmental impacts in IFs focus on processes that affect agriculture. Both temperature change from climate change and restraint on irrigated land area from water system stress affect agricultural yield. The agricultural model of IFs, in interaction with demographics and economics, represents the responses of production (positive) and demand and nutrition levels (negative) to any resultant price increases. That is only the beginning of the complex and extended causal chain system across the models of IFs. For example, negative impacts on nutrition/health and GDP per capita still further affect domestic instability and conflict potential with their own extended impact streams.

In addition to this process-based representation of climate change on agriculture, IFs relies on a statistically aggregated approach for impact of warming on sectors of the economy other than agriculture. A switch (***climeconimpsw***) turns on the impact of climate for the nonagricultural economy via the computation of the magnitude of economic damage (*CLIMECONIMP*) resulting from the change in global temperature (*WTEMP*) relative to that of the initial model year plus the degree of global change already experienced. The formulation is similar to the quadratic equation of cost-benefit models like FUND, DICE, and PAGE and computes the damage as a percentage of GDP, using linear and quadratic terms.

$$\begin{aligned} CLIMECONIMP_r &\\ &= \boldsymbol{climeconimplin} * (WTEMP - WTEMP_{t=1} + 1) \\ &+ \boldsymbol{climeconimpsq} * (WTEMP - WTEMP_{t=1} + 1)^2 \end{aligned}$$

The damage reduces value added (*VADD*) by sector, previously computed in the economic model.

$$VADD_{r,s} = VADDPrev_{r,s} * (1 - (CLIMECONIMP_r - CLIMECONIMP_{r,t=1})/100)$$

As discussed, it is possible that climate-related impacts are not only on annual production (with some future impact via reduced savings and investment) but also directly on capital stock and total factor productivity (*TEFF*), another economic stock term. IFs includes a parameter (***climeconimpstk***) that can be activated to represent the portion of economic damage that might affect productivity as previously calculated (*TEFFPrev*) in the economic model in years after the first (see Section 6.1.4.1).

$$TEFF = TEFFPrev_{r,s} * \left(1 - \frac{CLIMECONIMP_r}{100} * \boldsymbol{climeconimpstk}\right)$$

In addition to global warming and water stress, the presentation of the health model in Section 5.2 identified another process pathway of environmental impact in IFs. Quality of water and sanitation affects levels of diarrhea, which has implications for nutrition, especially of children. That health impact, like that of climate change on yield, has complex forward linkages and feedbacks in the larger model system. Nutrition levels affect childhood (including infant) mortality, and infant mortality in turn affects the probability of intrastate conflict. Conflict can lead to severe acute malnutrition thereby setting up a (vicious) positive feedback loop also involving negative impacts on economic growth.

8.1.4 Limitations

Other more enumerated paths of environmental impact could be added to IFs either as supplements to, or partial replacements of, those mentioned previously. For instance, it should be relatively simple to add a linkage between global warming and increases in energy demand for cooling.

Yet there is the risk of double counting of impacts when some are enumerated and some are aggregated. As noted, the specifically enumerated path of warming to agricultural yield and nutrition changes can lead in IFs to changes in health variables, including stunting and life expectancy, and those variables in turn affect economic productivity across the economy. Thus the combination of this causal logic with explicit representation and parameterization of economic impacts of warming on nonagricultural sectors in the manner of models like DICE raises the possibility of double counting some effects of warming on those sectors. Further, IFs represents forward linkages from economic impact, including changes in education attainment, that will have secondary effects that endogenously either supplement or offset the direct and simple specification of the economic impact of climate change. To compensate for possible double counting, it would be possible either to disable enumerated linkages within IFs or to weaken the more general specification of climate change impacts on nonagricultural sectors, but scaling would always be uncertain.

Most generally and very important, IFs does not deal well with some of the challenges that face all modeling of climate change impact. Specifically, IFs does not represent increased weather volatility or extreme events. Ongoing research on the economic impacts of droughts[14] and flooding related to such volatility increasingly provides a basis for their addition.

8.2 TECHNOLOGY

Technology poses special challenges for modeling because its impact is all pervasive across developmental issue areas and very difficult to represent quantitatively except as embedded in other change, whether that be improvement in health, economic growth, and agricultural yield, or reduction in the cost of renewable energy forms. That embedded character has led futurists outside of the modeling world to use a variety of mixed qualitative and quantitative

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[14] In personal correspondence and at the 10th annual meeting of the Integrated Assessment Model Consortium (December 5, 2017), Stephanie Waldhoff explained the analysis of drought in the GCAM model in the context of a project incorporating three paths of climate-to-yield impact: average temperature, droughts, and flooding.

techniques to think about the future of technology. For instance, the Delphi technique (Gordon and Helmer-Hirschberg, 1964, with ongoing use and refinement of real-time methodology by the Millennium Project[15]) draws on rounds of expert judgment to anticipate likely technological developments, while cross-impact analysis, also developed by Gordon and Helmer (Gordon, 1994), helps identify the interrelationships of technology with other variables. Such embedded representation tends also to be the manner of technology's treatment across other modeling platforms, albeit with a variety of endogenous and exogenous specifications.

8.2.1 Conceptualization and Treatment of Technology

Endogenous approaches include representing technological change as a function of investment in research and development (R&D) or learning by doing linked to past growth patterns and economies of scale. For some variables, such as efficiency of energy consumption, technological change may be a direct function also of the price of energy. Both endogenous and exogenous approaches can be combined with specification of backstop technologies that become economical and extensively available at sufficiently high price levels. Gillingham et al. (2007) summarized these different approaches to representing technology, indicated the selection among them in various IAMs (their Table 1, p. 31), and discussed relative strengths and weaknesses.

No approach is without weaknesses. Exogenous specification often overlooks the typically variable pace of technological advance (and adoption) at different stages of development. Endogenous response to investment in R&D can help model advance in technology in a specific sector, but it is difficult to identify the implications for other sectors of the competition for scarce resources, like scientific talent, and the possible intersectoral spillover effects gained or lost by shifting R&D. Scarcity of past data on technological advance, especially for newly developing technologies, challenges calibration of all approaches.

Specific issues associated with representation in IAMs also are important. Stanton et al. (2008, p. 16) noted that many optimizing models questionably assume decreasing returns to scale in production functions with technological advance, which helps ensure a unique equilibrium result. Similarly, Wilson and Grűbler (2011) pointed out that such models may put constraints on market penetration to limit model output change across parameter variation.

The work of Grűbler (1998) and Wilson and Grűbler (2011) has provided an important contextual understanding of technological advance, focused on that for clean energy technologies. They emphasized the coevolution of technology and its institutional and social context. Change in the latter is often very slow because of established demand technologies and usage patterns, with sunk costs related to both supply and demand. Further, technological change occurs in clusters of interacting advance in uses as well as provision, like those that have surrounded both the steam engine/coal and the electricity/petroleum energy systems. Thus energy system transformations have been century-long processes with formative (niche market), up-scaling, and growth phases. Although the thrust of their historically

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[15] See http://www.millennium-project.org/rtd-general/. Also used by TechCast Global at https://www.techcastglobal.com/.

contextual analysis cautions against expectations of dramatically rapid decarbonization, including that from the new renewables, it does not preclude extremely different scenarios in the long term. In fact, Wilson and Grűbler (2011, p. 25) noted approvingly that, while an analysis in 2000 of industrial carbon emissions across the dramatically different Special Report on Emission Scenarios created for the IPCC third assessment showed similar patterns through about 2025, the annual emissions in 2100 varied from about 5 to 30 gigatons.

8.2.2 Technology in IFs

IFs uses a mixture of endogenous and exogenous approaches to representing technology, and it embeds technology across a number of the models that comprise the human development, socioeconomic change, and biophysical issue groupings in IFs rather than treating it as a discrete and separate model.

In the health model, technology affects mortality via a time-related exogenous specification built on work and parameterization done by the World Health Organization (see Section 5.2.4.2). IFs does not represent technological change in education, where it could affect costs per student and/or quality of outcomes. IFs has, however, built a general index for the advance of the knowledge society that draws on five subsidiary indices that are collectively responsive to literacy, tertiary education, R&D, ICT extent (for which IFs also computes an index), and international economic integration.

In the economic model, the representation of technology (more generally multifactor productivity, or MFP) is extensive and complex (see Section 6.1.4.1). It begins with a core specification of time-related advance in the globally leading country and convergence by other countries based on GDP per capita at purchasing power parity. Multiple factors in the categories of human, social, physical, and knowledge capital generate additive or subtractive adjustments to the core rates. The end product is a net annual change in MFP that reflects what Gillingham et al. (2007, p. 8) characterize as the neoclassical growth approach to endogenous productivity.

The MFP approach applies, however, only to four of the six economic sectors in IFs, namely those in which Cobb-Douglas production functions directly determine value added in currency terms from capital, labor, and productivity (the four are raw materials, manufactures, services, and information/communications technology). The other two sectors, agriculture and energy, are physical models in IFs in which productivity advance affects appropriate physical production variables before they are converted to currency values and fed to the broader economic model. In agriculture, crop prices induce productivity-related change in an otherwise time-related basic growth rate of yield (initially tied to historical patterns), subject also to saturation and exogenous scenario assumption. In energy, prices similarly alter the rate of change in physical productivity of capital stock by energy type, which has an initial basis in historical patterns but is modified over time by both decreases in productivity with fossil resource exhaustion and exogenous assumptions concerning technological advance. On the demand side, energy efficiency improvements have core exogenous, time-related specifications, subject also to price-induced changes.

In the water model, exogenous parameters can control the efficiency of each category of demand. These augment changing intensity of water use in those same categories with price.

On a scenario basis, model users can make exogenous changes in technological advance across the various representations in IFs. For instance, one could parametrically represent Kondratieff long waves of economic advance (Kondratieff, 1926). Scenarios can more generally represent the discontinuous and disruptive sides of technology. In studies with IFs on the potential for very rapid and major life extension (Hughes et al., 2015) and on the economic benefits and risks of cyber technology and its vulnerability (Hughes et al., 2016; Zurich Insurance Group, 2015), the project has undertaken some important steps in looking at the impacts of technological discontinuities.

With respect to the latter, large-scale disruptive impact from artificial intelligence (AI) and robotics is highly probable this century, suggesting the need for further broadening of project horizons. To that end, the IFs team has begun to quantify and represent possible progress of AI in variations from narrow (e.g., Siri, Alexa, and other early personal assistants) to general (applications using reasoning and creativity) to superintelligence (intelligence challenging or surpassing that of humans) (see Scott et al., 2017). Even if AI's disruption manifests itself only in Schumpeter's (1942) ultimately positive vision of creative destruction of current economic and social patterns, it will affect huge numbers of jobs and lives during the transition. For example, Winick (2018) summarized 18 different estimates of labor impact from automation. Among those is one cited especially often, a McKinsey report (Manyika et al., 2017) estimating that 400–800 million jobs could be automated globally by 2030. The power of such automation may be working synergistically with the emergence of large network effects that support the rise and oligopolistic or even monopolistic power of huge new technology companies. Among the possible interrelated consequences are increasing share of GDP accruing to companies relative to workers, slowing increases of wages, and either a hollowing out of the labor market as mid-level skills are automated or a broader loss of jobs below the most high-skilled level. All such effects would raise within country inequality, with significant implications for human and social development. Like the impacts of environmental change, such technological disruption very much deserves attention in global models.

8.2.3 Limitations

Technological change is so critical to long-term thinking that the scattering of access points for alternative assumptions about it across the various component models of the IFs system has disadvantages for those wishing to focus analysis on it. One can imagine an integrated form in the user interface that made focus on technology easier, perhaps even facilitating connection to approaches for thinking about technological change such as the real-time Delphi approach.

8.3 CONCLUDING REMARKS

The limitations noted in this chapter concerning treatment of highly important inter-issue linkages and disruptive forces both within IFs and the broader global modeling effort create a logical bridge to stepping back and reflecting more generally on the strengths and weaknesses of global modeling, how scenarios address uncertainty, and how the enterprise may advance in the coming decades. That stepping back is the central purpose of the next and final chapter.

References

Anthoff, D., Tol, R.S.J., 2014a. The Climate Framework for Uncertainty, Negotiation and Distribution (FUND): Technical Description, Version 3.9. Use FUND3.9 Documentation download option from http://www.fund-model.org/versions.

Anthoff, D., Tol, R.S.J., 2014b. The Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Tables, Version 3.9. Use FUND3.9 Tables download option from http://www.fund-model.org/versions.

Anthoff, D., Nicholls, R.J., Tol, R.S.J., 2010. The economic impact of substantial sea-level rise. Mitig. Adapt. Strateg. Glob. Chang. 15 (4), 321–335. https://dx.doi.org/10.1007/s11027-010-9220-7.

Arent, D.J., Tol, R.S.J., 2014. Key economic sectors and services. In: Intergovernmental Panel on Climate Change, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report. Cambridge University Press, New York, NY, pp. 659–708.

Bellemare, M.F., 2015. Rising food prices, food price volatility, and social unrest. Am. J. Agric. Econ. 97 (1), 1–21. https://dx.doi.org/10.1093/ajae/aau038.

Birkmann, J., Cutter, S.L., Rothman, D.S., Welle, T., Garschagen, M., van Ruijven, B., et al., 2013. Scenarios for vulnerability: opportunities and constraints in the context of climate change and disaster risk. Clim. Chang. 133 (1), 53–68. https://dx.doi.org/10.1007/s10584-013-0913-2.

Bonen, A., Semmler, W., Klasen, S., 2014. Economic Damages from Climate Change: A Review of Modeling Approaches. Working Paper no. 2014-3. Schwartz Center for Economic Policy Analysis, The New School for Social Research, New York, NY.

Burke, M.B., Miguel, E., Satyanath, S., Dykema, J.A., Lobell, D.B., 2009. Warming increases the risk of civil war in Africa. Proc. Natl. Acad. Sci. U. S. A. 106 (49), 20670–20674. https://dx.doi.org/10.1073/pnas.0907998106.

Burke, M., Davis, W.M., Diffenbaugh, N.S., 2018. Large potential reduction in economic damages under UN mitigation targets. Nature 557, 549–553.

Carleton, T.A., Hsiang, S.M., 2016. Social and economic impacts of climate. Science 353 (6304), aad9837. https://dx.doi.org/10.1126/science.aad9837.

Cline, W.R., 2007. Global Warming and Agriculture: Impact Estimates by Country. Center for Global Development and Peterson Institute for International Economics, Washington, DC.

Dietz, S., Stern, N., 2015. Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. Econ. J. 125 (583), 574–620. https://dx.doi.org/10.1111/ecoj.12188.

European Academies Science Advisory Council (EASAC), 2018. Extreme Weather Events in Europe—Preparing for Climate Change Adaptation: An Update on EASAC's 2013 Study. EASAC Statement available at https://easac.eu/fileadmin/PDF_s/reports_statements/Extreme_Weather/EASAC_Statement_Extreme_Weather_Events_March_2018_FINAL.pdf.

Field, C.B., Barros, V.R., Mach, K.J., Mastrandrea, M.D., 2014. Technical summary. In: Intergovernmental Panel on Climate Change, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report. Cambridge University Press, New York, NY, pp. 35–94.

Fjelde, H., 2015. Farming or fighting? Agricultural price shocks and civil war in Africa. World Dev. 67 (March), 525–534. https://dx.doi.org/10.1016/j.worlddev.2014.10.032.

Gillingham, K., Newell, R.G., Pizer, W.A., 2007. Modeling Endogenous Technological Change for Climate Policy Analysis. RFF Discussion Paper 07-14. Resources for the Future, Washington, DC. http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-07-14.pdf.

Gordon, T.J., 1994. Cross-Impact Method. Futures Research Methodology. American Council for the United Nations University (AC/UNU) Millennium Project, Washington, DC. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.202.7337&rep=rep1&type=pdf.

Gordon, T.J., Helmer-Hirschberg, O., 1964. Report on a Long-Range Forecasting Study. RAND Paper no. P-2982. RAND Corporation, Santa Monica, CA. https://www.rand.org/pubs/papers/P2982.html.

Grűbler, A., 1998. Technology and Global Change. Cambridge University Press, Cambridge, UK.

Hansen, J., Sato, M., Ruedy, R., 2012. Perception of climate change. Proc. Natl. Acad. Sci. U. S. A. 109 (37), E2415–E2423. https://dx.doi.org/10.1073/pnas.1205276109.

Hendrix, C.S., Haggard, S., 2015. Global food prices, regime type, and urban unrest in the developing world. J. Peace Res. 52 (2), 143–157. https://dx.doi.org/10.1177/0022343314561599.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Richard S. J. Tol, et al., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc. Natl. Acad. Sci. U. S. A. 111 (9), 3292–3297. https://dx.doi.org/10.1073/pnas.1222469111.

Hope, C., 2011. The PAGE09 Integrated Assessment Model: A Technical Description. Cambridge Judge Business School. Working Paper Series 4/2011. University of Cambridge, Cambridge, UK. https://www.jbs.cam.ac.uk/fileadmin/user_upload/research/workingpapers/wp1104.pdf.

Hughes, B.B., Kuhn, R., Margolese-Malin, E.S., Rothman, D.S., Solórzano, J.R., 2015. Opportunities and challenges of a world with negligible senescence. Technol. Forecast. Soc. Chang. 99 (October), 77–91. https://dx.doi.org/10.1016/j.techfore.2015.06.031.

Hughes, B.B., Bohl, D., Irfan, M., Margolese-Malin, E., Solórzano, J.R., 2016. ICT/cyber benefits and costs: reconciling competing perspectives on the current and future balance. Technol. Forecast. Soc. Chang. 115 (February), 117–130. https://dx.doi.org/10.1016/j.techfore.2016.09.027.

Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Kondratieff, N.D., 1926. Die Langen Wellen der Konjunktur. Achiv Sozialwissensch. Sozial. 56 (3), 573–609. Translated by Wolfgang F. Stolper and published in 1935 as "The Long Waves in Economic Life" in The Review of Economic Statistics 17(6): 105–115.

Koren, O., Bagozzi, B.E., 2016. From global to local, food insecurity is associated with contemporary armed conflicts. Food Sec. 8 (5), 999–1010. https://dx.doi.org/10.1007/s12571-016-0610-x.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. U. S. A. 105 (6), 1786–1793.

Manyika, J., Lund, S., Chui, M., Bughin, J., Woetzel, J., Batra, P., et al., 2017. Jobs Lost, Jobs Gained: Workforce Transitions in a Time of Automation. McKinsey Global Institute Report. McKinsey & Company, New York, NY. https://www.mckinsey.com/~/media/McKinsey/Global%20Themes/Future%20of%20Organizations/What%20the%20future%20of%20work%20will%20mean%20for%20jobs%20skills%20and%20wages/MGI-Jobs-Lost-Jobs-Gained-Report-December-6-2017.ashx.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens III, W.W., 1972. Limits to Growth. Universe Books, New York, NY.

Mendelsohn, R.O., Morrison, W.N., Schlesinger, M.E., Andronova, N.G., 2000. Country-specific market impacts of climate change. Clim. Chang. 45 (3–4), 553–569. https://dx.doi.org/10.1023/A:1005598717174.

National Academies of Sciences, Engineering, and Medicine, 2017. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. National Academies Press, Washington, DC. https://dx.doi.org/10.17226/24651.

Nordhaus, W.D., 2016. Projections and Uncertainties About Climate Change in an Era of Minimal Climate Policies. Cowles Foundation Discussion Paper no. 2057. Cowles Foundation for Research in Economics, Yale University, New Haven, CT. http://cowles.yale.edu/sites/default/files/files/pub/d20/d2057.pdf.

Nordhaus, W.D., Moffat, A., 2017. A Survey of Global Impacts of Climate Change: Replication, Survey Methods, and a Statistical Analysis. Cowles Foundation Discussion Paper No. 2096. Cowles Foundation for Research in Economics, Yale University, New Haven, CT. http://cowles.yale.edu/sites/default/files/files/pub/d20/d2096.pdf.

Nordhaus, W., Sztorc, P., 2013. DICE 2013R: Introduction and User's Manual. Department of Economics, Yale University, New Haven, CT. http://www.econ.yale.edu/~nordhaus/homepage/documents/DICE_Manual_103113r2.pdf.

Olsson, L., Opondo, M., Tschakert, P., 2014. Livelihoods and poverty. In Intergovernmental Panel on Climate Change, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Cambridge University Press, New York, NY, pp. 793–832.

Organisation for Economic Co-operation and Development (OECD), 2015. The Economic Consequences of Climate Change. OECD Publishing, Paris, France. https://dx.doi.org/10.1787/9789264235410-en.

Organisation for Economic Co-operation and Development (OECD), 2016. The Economic Consequences of Outdoor Air Pollution. OECD Publishing, Paris, France. https://dx.doi.org/10.1787/9789264257474-en.

Rees, W.E., Wackernagel, M., 2013. The shoe fits, but the footprint is larger than earth. PLoS Biol. 11(11)e1001701. https://dx.doi.org/10.1371/journal.pbio.1001701.

Rockström, J., Steffen, W., Noone, K., Åsa, P., Stuart Chapin III, F., Lambin, E., et al., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 (2) 33 p, www.jstor.org/stable/26268316.

Rose, S.K., Diaz, D.B., Blanford, G.J., 2017. Understanding the social cost of carbon: a model diagnostic and intercomparison study. Clim. Change Econ. 8 (2), unpaginated. https://dx.doi.org/10.1142/S2010007817500099.

Roson, R., van der Mensbrugghe, D., 2012. Climate change and economic growth: impacts and interactions. Int. J. Sustain. Econ. 4 (3), 270–285. https://dx.doi.org/10.1504/IJSE.2012.047933.

Schleussner, C.-F., Donges, J.F., Donner, R.V., Schellnhuber, H.J., 2016. Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. Proc. Natl. Acad. Sci. U. S. A. 113 (33), 9216–9221. https://dx.doi.org/10.1073/pnas.1601611113.

Schumpeter, J.A., 1942. Capitalism, Socialism, and Democracy. Harper & Brothers, New York, NY.

Scott, A.C., Solórzano, J.R., Moyer, J.D., Hughes, B.B., 2017. Modeling Artificial Intelligence and Exploring Its Impact. Working Paper. Frederick S. Pardee Center for International Futures, University of Denver, Denver, CO. http://pardee.du.edu/sites/default/files/ArtificialIntelligenceIntegratedPaper_V6_clean.pdf.

Stanton, E.A., Ackerman, F., Kartha, S., 2008. Inside the Integrated Assessment Models: Four Issues in Climate Economics. SEI Working Paper WP-US-0802. Stockholm Environment Institute, U.S. Center, Somerville, MA.

Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge, UK.

Tol, R.S.J., 2009. The economic effects of climate change. J. Econ. Perspect. 23 (2), 29–51. https://dx.doi.org/10.1257/jep.23.2.29.

Urdal, H., 2005. People vs. Malthus: population pressure, environmental degradation, and armed conflict revisited. J. Peace Res. 42 (4), 417–434. https://dx.doi.org/10.1177/0022343305054089.

Űrge-Vorsatz, D., Cabeza, L.F., Serrano, S., Barreneche, C., Petrichenko, K., 2015. Heating and cooling energy trends and drivers in buildings. Renew. Sust. Energ. Rev. 41, 85–98. https://dx.doi.org/10.1016/j.rser.2014.08.039.

van der Mensbrugghe, D., 2013. Modeling the global economy—forward looking scenarios for agriculture. In: Dixon, P.B., Jorgensen, D.W. (Eds.), Handbook of Computable General Equilibrium Modeling. In: Vol 1B. North-Holland, Oxford, UK; Waltham, MA, pp. 933–994. https://dx.doi.org/10.1016/B978-0-444-59568-3.00014-6.

Verburg, P.H., Dearing, J.A., Dyke, J.G., van der Leeuw, S., Seitzinger, S., Steffen, W., Syvitski, J., 2016. Methods and approaches to modelling the anthropocene. Glob. Environ. Chang. 39 (July), 328–340. https://dx.doi.org/10.1016/gloenvcha.2015.08.007.

von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., et al., 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison. Agric. Econ. 45 (1), 3–20. https://dx.doi.org/10.1111/agec.12086.

Weitzman, M.L., 2009. On modeling and interpreting the economics of catastrophic climate change. Rev. Econ. Stat. 91 (1), 1–19. https://dx.doi.org/10.1162/rest.91.1.1.

Wilson, C., Grűbler, A., 2011. Lessons from the history of technological change for clean energy scenarios and policies. Nat. Res. Forum 35 (3), 165–184. https://dx.doi.org/10.1111/j.1477-8947.2011.01386.x.

Winick, E., 2018. Every study we could find on what automation will do to jobs, in one chart. MIT Technol. Rev. January 25, unpaginated. https://www.technologyreview.com/s/610005/every-study-we-could-find-on-what-automation-will-do-to-jobs-in-one-chart/.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D.B., Huang, Y., et al., 2017. Temperature increase reduces global yields of major crops in four independent estimates. Proc. Natl. Acad. Sci. U. S. A. 414 (35), 9326–9331. https://dx.doi.org/10.1073/pnas.1701762114.

Zurich Insurance Group, 2015. Overcome by Cyber Risks? Economic Benefits and Costs of Alternate Cyber Futures. Risk Nexus report in collaboration between Zurich Insurance, the Atlantic Council, and the Frederick S. Pardee Center for International Futures. Zurich Insurance Group, Zurich, Switzerland. http://publications.atlanticcouncil.org/cyberrisks//risk-nexus-september-2015-overcome-by-cyber-risks.pdf.

CHAPTER

9

Looking Ahead: Global Models and the IFs System

What are the possible future sizes of global, regional, and country-specific populations, their age-sex compositions and education levels, the number of children women will have, the pattern of likely deaths from different cause groupings? What are the possible growth patterns of the world's economy, the contributions of labor, capital, and productivity to those, the changing nature of governance and government finances around the world? What are the major environmental challenges that we face, across land, air, and sea, and how might the growing needs for food and energy affect those? What options do we have for advancing toward each of the Sustainable Development Goals and how much leverage might they give us? How might changes in these issue areas affect each other across time?

Global models (with all their supporting systems, especially new databases) help us address these and related questions much better than we could prior to the emergence of the first world models in the early 1970s. Progress has been dramatic in the ability of models to help us understand where we are in the unfolding of a wide range of interacting global transitions, where we seem to be going, the opportunities and challenges we face, and how we might alter current patterns of change. Yet because models are simplified and sometimes competing representations of reality, analyses with them will invariably be uncertain. We must keep in mind the purposes of global models: to help us individually and collectively think about the future, to prepare for it even in the face of great uncertainty, and to contribute to shaping it (recognizing both uncertainties with respect to dynamics of change and contention about what is desirable in that shaping).

This chapter shifts focus specifically to the issue of how well modelers do in understanding long-term global change and how we might improve, again with extra attention to the International Futures (IFs) system in the context of the larger effort. First, building on earlier chapters, this chapter reflects on understanding of the dynamics of global change within and across issue areas, extracting some general thoughts about the broad areas of agreement among modelers but also noting the uncertainties. In the aggregate, those uncertainties can give rise to very different integrated perspectives concerning the likely and even possible playing out of global change across the century. Second, this chapter surveys some of the scenario literature

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concerning global change, in part to consider whether and how it treats those uncertainties. Third, this chapter considers the use of scenarios (which often frame our general understanding of alternative futures) in policy analysis so as to support consideration of more specific policy and social choices. Finally, it concludes with thoughts on the greatest challenges to continued advance of global modeling and how progress might be made.

9.1 THINKING ABOUT THE FUTURE: UNCERTAINTIES

This volume has analyzed modeling and presented selective projections from multiple efforts, proceeding by issue area and grouping the issues roughly by human development, social change, and environmental sustainability. Fig. 9.1 provides an overview of those issue areas and groupings, differing little from the organization of Chapters 5–8 (and not much from Fig. 4.1, the block diagram of the IFs system). It also points to just a few of the ongoing disruptions and potential wild cards that add much to our uncertainty.

9.1.1 Foundations of Alternative World Views and Future Scenarios

Looking back across the volume, the similarities of perspective across most global modeling projects concerning the current path of change within the three issue domains of Fig. 9.1,

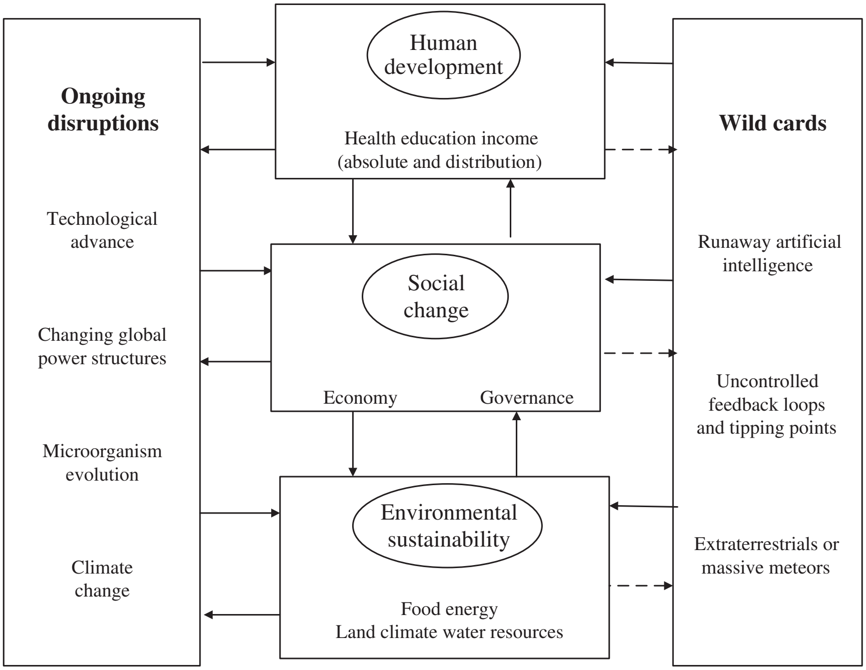

FIG. 9.1 **Issues of future interest for humanity and examples of forces creating uncertainty.**
Note: Humans have less control over wildcards than over disruptive forces (hence the dashed causal arrows); those in the figure are only illustrations from large sets of both. Source: Author.

and where the greatest uncertainties are, is rather impressive. Yet there are important differences of understanding within each domain. Most striking, however, are the uncertainties and differences of perspective concerning how the interactions of the three domains will play out. Collectively, those differences lay the foundations for alternative worldviews (in mental models as well as computerized ones) concerning long-term human prospects. We return to that tension in broad perspective after considering the three domains separately.

Consider human development. Collectively, the reference or Base Case scenarios of modelers seem relatively confident about likely demographic change patterns, including continued fertility reduction in low-income countries and large-scale global aging of societies. Projections differ somewhat, mostly because of different formulations for fertility, both in the rates of fertility reduction in societies where fertility remains high and in the degree to which rates might stay below replacement levels in higher-income societies. Modelers as a group recognize the possibility of major breakthroughs in health and longevity, the extent of which is now a very considerable uncertainty in human development. A steady slog toward increased longevity, with at least somewhat healthier aging, appears the most common anticipation. Similarly, few analysts seem to anticipate major changes in the rapid progression of humanity toward higher levels of formal and, increasingly, informal education. While the expectation of continued rise in human wellbeing is deeply rooted in Western idealism going back to at least the Renaissance, it is reinforced by the experience of more than two centuries. When analysts do express skepticism about continued progress in wellbeing, the reasons generally reflect the expected challenges of social and sustainable development.

Consider social change. Images of the future here are more mixed. Collectively again, the base or reference scenarios of modelers widely expect continued economic growth in per capita, not just absolute, terms. Although diminishing workforce share of the total population or productivity growth may reduce rates of per capita advance, those rates are generally not expected to slow dramatically; technological change could even accelerate them. Technology's impact on growth and on inequality (as well as energy system transformation) is among the very greatest uncertainties. While the collective wisdom concerning convergence of developing economies with higher-income ones has swung in this century from considerable earlier skepticism to substantial expectation of it, there seems less consensus on potential for convergence by very low-income and socially fragile societies. With respect to broader sociopolitical and cultural change, however, we have seen that even agreeing on concepts and measures becomes more difficult, and it is hard to find, much less compare, long-term quantitative analyses. While expectations of progressive human development tend to give rise to those of progressive social change, including reduction in state fragility and advance of democratization, there is hardly a strong consensus around the rates or even the likelihood of such progression. Technology is also enhancing the power of nongovernmental forces, including social media and terrorism, to disrupt governance. Moreover, the issue is not simply one of the general character of governance but also of the ability of societies to create and implement specific policy approaches to address a wide range of problems. Those problems include mixed economic growth prospects, large-scale inequality, and, once again, environmental challenges. They also extend to international politics and the need for smooth handling of (all but inevitable) global power transitions.

Consider environmental sustainability. We saw in Chapter 7 that the reference case scenarios of most agriculture and food models agree with respect to the improvement of global nutrition, although they do not anticipate the eradication of undernutrition on the SDG timetable of 2030. Similarly, energy models anticipate demand and usage per capita to rise globally, with developing countries converging toward patterns of high-income ones. It is, however, as it was already in the 1970s, about the availability of at least some resources and the impact of human activity on the environment that modelers of biophysical systems tend to be very concerned and uncertain. Water is a special concern on the input side, and land (with good soil) for crops and grazing is also high on the list. With respect to outputs of human activity, greenhouse gas emissions from fossil fuels, cement production, and land use draw the greatest attention and concern, with current path scenarios of studies almost never seeing us on course to safely limit global warming this century. In addition to the greater pessimism of reference scenarios, uncertainty around the potential impacts of environmental change tends to exceed that around human development and social change.

This sketch of the general character of common base case or reference perspectives across the three issue groupings raises a tension. Progress in human and social development is generally expected, but it is dependent on at least reasonably positive futures for human relationships with the environment. However, the level of concern around the future of the environment is very high, so much so as potentially even to call into question the maintenance of current progress with respect to human wellbeing and the somewhat more mixed success in collective interaction. In light of this, what do we really think about global futures?

9.1.2 Elaboration of Alternative World Views and Future Scenarios

The question becomes sharper when we use the block diagrams of Figs. 9.2 and 9.3 to sketch two very different images of the future across the issue groupings (many variations are possible). These images come less from global modelers than from the broader ecosystem of those who think about the future and those who have some role in shaping it. Fig. 9.2 lays out a simplified image that draws upon some of the great concerns of both the early world modelers of the 1970s and 1980s and the integrated assessment modelers of more recent decades. The famines and energy crises of the 1970s (as well as major increases in urban air and general water pollution) heavily influenced the early modelers, who anticipated energy and food shortages that would lead to downturns in economies and human wellbeing through mechanisms generally not well elaborated but implicitly involving governance failures and conflict as well as direct effects on nutrition and health. The rise of concerns about climate change and water shortages have directed significant attention by integrated assessment modelers to those issues, still with often limited formal elaboration of their broader impacts, but typically with concern for their effects on progress toward food security and more generally for improvements in human and social development systems.

A broader context for such thinking lies in historical analysis of civilizations that have collapsed in part due to natural or induced environmental change in interaction with socially based inability to adapt (Diamond, 2005; Toynbee, 1934–1961). Tipping points are a special kind of major system disruption, generated sometimes by external shocks but often by accumulated pressures that destroy an existing equilibrium. Many such tippings involve activation of a vicious positive feedback loop to dominance, like the mutually destructive cycle of undernutrition and domestic conflict (see again Fig. 9.2). We generally do not have great

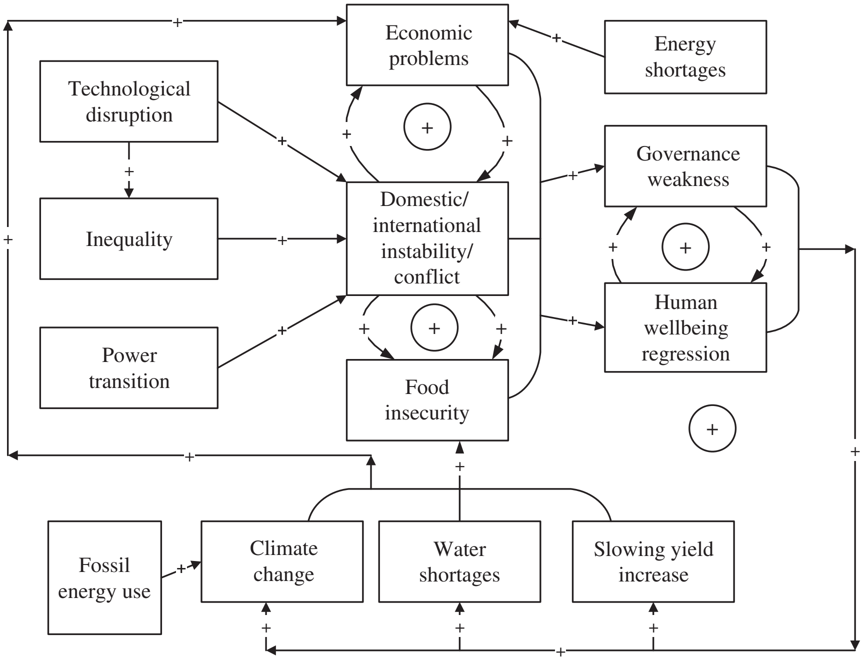

FIG. 9.2 **Dynamics that characterize environmentally pessimistic worldviews.**
Note: Environmentally concerned portrayals of global change generally focus on selected dynamics rather than trying to treat all or even most of those shown here. Source: Author.

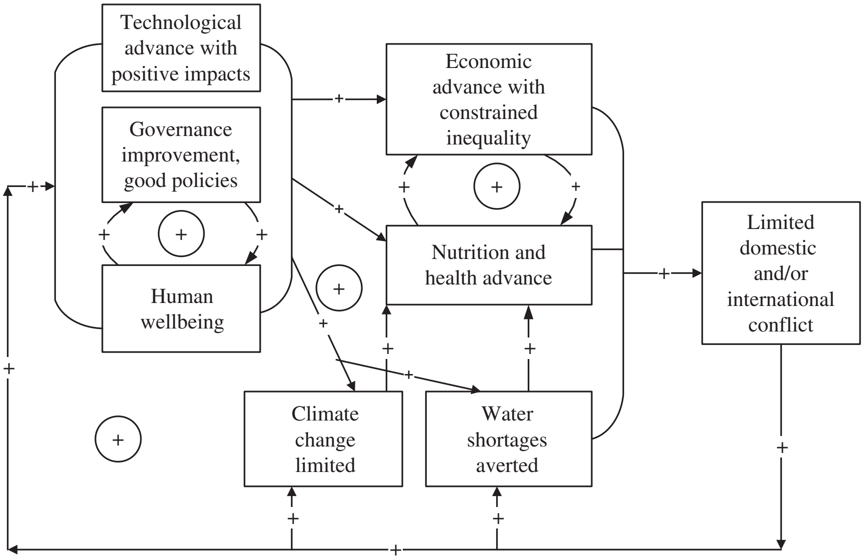

FIG. 9.3 **Dynamics that characterize developmentally optimistic worldviews.**
Note: Positive images of global change generally focus on selected dynamics, not all. Source: Author.

confidence in model formulations of tipping points and representations of how they might begin or ultimately play out (e.g., indefinite state failure or ultimate recovery). The modeling underlying *Limits to Growth* (Meadows et al., 1974) did nonetheless represent tippings that led to collapse of systems, but was met with significant criticism. It is not clear whether that criticism contributed to the reluctance to include tipping points that characterizes most contemporary modeling out of concern that it might undercut the credibility of other analysis. Most likely, contemporary modelers, including those in the IFs project, seldom incorporate such tipping points because they have the character of wild card low-probability but high-impact occurrences; there are too many of them (e.g., see Lenton et al., 2008 for a discussion of several possible in climate change) and they are too poorly understood to treat confidently with model formulations. Even scenario analysis of them is challenging.

But consider the much more optimistic image of Fig. 9.3, more consistent with what have come to be called the New Optimists. Simon (1981) already challenged the early world modelers with his image of global progress driven heavily by more educated populations contributing to rapid technological advance. In a similar vein, Ridley (2011) more recently described a future heavily enhanced by technology progress and what he called "cultural evolution" (linked to human and social development). Pinker (2011, 2018) has elaborated data, relationships, and causal paths of human progress, and a collection of studies included in Lomborg (2013) found that costs of nearly all global problems as a percentage of GDP have declined since 1900—and in almost all cases will decline further through 2050 (global warming is an exception).[1] Whereas at one time such optimists might have merited a label simply as technological enthusiasts, that is no longer completely appropriate. The New Optimists have the advantage of having seen the tremendous progress in education, health, and poverty reduction during the period of the Millennium Development Goals (and earlier); they have also seen significant technology and policy advances in energy, agriculture, and environmental arenas over recent decades, including against water and urban air pollution in high-income countries.

Distinct from the New Optimists, but also sharing more positive views about global futures, are many in the more prescriptive foresight community who focus much attention on, and often confidence in, human agency as the driving force in consciously creating better futures. Gidley (2017), for example, reviewed the long history of thinking about the future and argued that there are two dominant perspectives today. The first she called technotopian, which she identified as putting technological enhancement of human capabilities on center stage. The second she labeled human-centered, viewing humans as "consciously evolving, peaceful agents of change with a responsibility to maintain the ecological balance …" (Gidley, 2017, p. 101).

Many (if not most) analysts and global modelers would reject both worldviews as oversimplified and argue that each offers some insight in how a complicated future will unfold. Yet the differences between these two perspectives help us identify the uncertainties that

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[1] In part lacking the organizational structures (and large research community base) of their more environmentally pessimistic counterparts, the New Optimists are more heavily visible in columns and news stories (e.g., Oliver Burkeman, "Is the World Really Better than Ever?" *The Guardian,* July 28, 2017) than in formal modeling circles. An exception is the Lomborg (2013) edited volume of studies, including IAMs, using quantitative research.

we face and that shape scenario analysis. As Figs. 9.2 and 9.3 also suggest, those uncertainties generally fall into two categories:

1. The possibility that the environmentally pessimistic perspective could be wrong about the extent of environmental damage that the current path will generate or about the consequences for human wellbeing that such damage might have. Global modelers will never deny that we can be wrong about either damage extent or consequences. We will also emphasize, however, that errors in understanding of our current path and representation of it in models could be in either direction, and that our use of models should include sensitivity analysis with respect to such possible errors. Focusing only on the possibility that the errors exaggerate problems would be wishful thinking, just as focusing only on the possibility that they underestimate them could be unduly alarmist. However, the precautionary principle and natural human risk aversion suggest the desirability of extra attention to error of underestimation, especially in light of unknowns such as possible tipping points.
2. The extent to which human agency can help us limit environmental change and damage. Consideration of that potential tends to focus on three thrusts related to human action:
    - Voluntarily undertaking lifestyle changes that reduce our environmental footprint, such as lowering consumption levels or consuming more selectively, recycling what we extract from the environment, and reducing population growth.
    - Strengthening institutions and governance as foundations for policy choices that encourage or require mitigating damage and improving adaptation (including lifestyle changes). There is, of course, considerable debate about the impact of some policy orientations, including the degree to which reliance on markets helps solve or exacerbates problems, and these uncertainties can also show up in scenario analysis.
    - Accelerating technological progress both to limit damage and to adapt to it. Although technology advance is a product of human agency, policy decisions cannot always control its pace or even its possibility as fully as they can many other path changes. There is an element of *deus ex machina* in technological advance that also makes it a candidate for both wishful thinking and underestimation, so it needs special attention in framing uncertainty.

As we move into a discussion of model use via scenario analysis, we will repeatedly see the influence of both categories of uncertainty, including all three manifestations of human agency.

9.2 EXPLORING UNCERTAIN FUTURES: SCENARIOS

Scenarios are elaborated stories about the possible playing out of causal dynamics (see Section 2.5.1). In models, scenarios emerge from a set of formulations (within structures) and parameters introducing combinations of alternative assumptions or understandings. The baseline or current path projection of a model is itself such a story. The discussion of major uncertainties in the previous section identified many of the key elements that shape alternative broad “framing” (also called “exploratory”) scenarios. The discussion that follows will also identify “prescriptive” and “policy intervention” scenarios, which call for or explore particular patterns of human agency. In addition to a base case or current path, scenario sets sometimes include a dystopian future to avoid (which might actually be the current path), and then a vision scenario.

9.2.1 Current Path, Reform, and Transformation: The Global Scenario Group

One of the early and most influential long-term global scenario development projects has been that of the Global Scenario Group (GSG) set up in 1995 by the Tellus Institute and the Stockholm Environment Institute and linked to the PoleStar forecasting project (see Section 3.1.3). GSG put forward three classes or families of broad framing or exploratory scenarios that exemplify the distinction between current path, dystopian, and visionary futures. Specifically, their scenarios are: Conventional Worlds (including a variant focused on Market Forces and one involving Policy Reform), Barbarization (including Fortress World and Breakdown variants, with combinations of authoritarian repression and conflict), and Great Transition (including an Eco-Communalism variant in which humans choose more modest and resilient lifestyles and a New Sustainability Paradigm) (see Gallopín et al., 1997; Raskin et al., 1998, 2002, 2010).

As the earlier discussion suggested with respect to the uncertainties that frame scenarios, primary forces differentiating GSG scenarios revolve around market, governance/policy, and citizen behavior variables (although in this case not technology). The attention to human behavior deserves special comment. Raskin and the GSG have made bottom-up change in human lifestyle front and center in their prescriptive visionary analysis, and clearly the Great Transition, heavily influenced by it, is their desired future.[2]

The distinction between GSG's Policy Reform scenario (within the Conventional Worlds family) and the scenarios in the Great Transition family is important. Scenario analysis like that of Policy Reform tends to focus on bending curves of change, but not breaking them. Much policy analysis in the IFs project has explored what I have long called "aggressive but reasonable" interventions to the current path of the Base Case, generally looking across the world and historically to scale the magnitude of aggressive policy change.

In contrast, large-scale prescriptive scenarios like Great Transition grow out of belief that either (1) global problems are so severe that a major break with past agent behavior patterns is necessary or (2) disruptive forces such as technological change will break past patterns—or both. A futurist community exists that is often skeptical that IAMs can represent such transformational change. It has frequently preferred to use more qualitative approaches that often combine envisioning transformed futures with advocating and sometimes elaborating action to build desired versions (Gidley, 2017; also Miller, 2018 and Poli, 2010). The GSG, with one eye on the quantitative side and one on dramatic change, has attempted to bridge this divide.

van Vuuren et al. (2012) traced how the GSG scenario set has strongly influenced many subsequent scenario studies. They noted that variants of these scenarios can be seen in the World Water Council's World Water Vision in 1999–2000; the first Organisation for Economic Co-operation and Development's Environmental Outlook in 2001; the Intergovernmental Panel on Climate Change's greenhouse gas mitigation assessment in 2001; the UN

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[2] See the elaboration of the GSG's prescriptive element and rationale for it at https://www.greattransition.org/publication/a-great-transition-where-we-stand.

Environment Programme's third and fourth Global Environment Outlook reports in 2002 and 2007; the Millennium Ecosystem Assessment (2005); and the standard scenario set distributed with the IFs system.

9.2.2 Selected Scenario Analyses Building on the GSG Work

Millennium Ecosystem Assessment (MEA). The title of the Millennium Ecosystem Assessment (2005) report, *Ecosystems and Human Well-Being*, identified its central focus on human wellbeing (framed in terms of the support for it from ecosystem services). The report also addressed the key role of sociopolitical systems (framed in terms of the necessary contributions from institutions, governance, and policies to protect ecosystems and their service contributions). The MEA scenario analysis through 2050 (sometimes 2100) drew upon information from models (especially IMAGE) as well as from literature, data sets, and, especially, a very wide range of experts.

The MEA's four scenarios had links to, but also considerable variation from, those of the GSG. Global Orchestration incorporated many elements of Conventional Worlds, and Order from Strength was a relative of Barbarization. Adapting Mosaic (the scenario most like the GSG's Great Transition in terms of its long-term impact on enhancing the provisioning, regulating, and cultural impacts of ecosystem services) looked to local level activity but also heavily emphasized institutions, management, and political activity. TechnoGarden, with its attention to encouragement of environmentally appropriate technological advance, was also very positive (except for the cultural impacts), but stepped well beyond the GSG grouping, which downplayed technological fixes.

Global Environment Outlook (GEO). The UN Conference on Environment and Development in 1992 (the Earth Summit, which established the UN's Agenda 21 action plan) set in motion the Global Environment Outlook (GEO) series of reports from the United Nations Environment Programme (UNEP). Several GEOs have drawn on the work of the GSG, including qualitative use of their scenarios by GEO-1 in 1995. Quantitative representations of the GSG work also supported the third and fourth Global Environment Outlooks. Chapter 9 of GEO-4 (Rothman et al., 2007) used a set of scenarios named Markets First, Policy First, Security First, and Sustainability First (the first two related again to Conventional Worlds, the third to Barbarization but with more focus on breakdown of global connections than on overt conflict, and the last to the Great Transition). GEO-4 presented a very wide range of projections across the four scenarios and across the three issue domains of this volume (without quantifications of sociopolitical change, however). The sources of driver variation across the GEO scenarios were wide. GEO-4's own categorization of the drivers (Rothman et al., 2007, pp. 402–404) was as follows: institutional and sociopolitical frameworks; demographics; economic demand, markets, and trade; scientific and technological innovation; and value systems.

GEO-4's analysis drew most heavily on the IMAGE suite and IFs, and to a lesser degree WaterGap modeling results (also some from IMPACT, AIM, and other models discussed in Sections 3.2.2 and 7.6.3). It provided an especially comprehensive portrayal of prospects around long-term global change. In the course of its support for GEO-4, the IFs project replicated the four GEO-4 scenarios and has continued to package them as a set available to users of successive IFs versions.

9.2.3 Other Important Scenario Studies

Multiple OECD analyses. The Organisation for Economic Co-operation and Development has produced a number of long-term economic and/or environmental outlook studies since 2001, including *Environmental Outlook to 2030* (OECD, 2008) and *Environmental Outlook to 2050* (OECD, 2012), both of which cast wide nets across socioeconomic and environmental variables. Both outlooks used the OECD's own ENV-Linkages model and teamed with the PBL Netherlands Environmental Assessment Agency for analysis from the IMAGE suite. Significant focus targeted so-called red light environmental issues: climate change, biodiversity, water, and the health impacts of pollution. Socioeconomic projections were used to drive environmental ones.

The studies contrasted baseline and policy option scenarios (in the form of intervention sets). Focusing on the second study, in its Baseline (current path) scenario the OECD (2012, pp. 46–58) anticipated for 2050 the addition of 2.2 billion people relative to 2010, with an urbanization rate of 70%; a near quadrupling of global GDP, with convergence of developing countries toward higher income ones[3]; a growth of energy demand/supply by 80% with a fossil fuel share remaining near 85%[4]; a peak in use of land for agriculture before 2030 and a growth in total forest area (with a decline in primary forest); increase in water demand by 55%, with jumps in manufacturing demand by 400%, thermal electricity generation use of water by 140%, and domestic use by 130%, thereby somewhat reducing use for irrigation. Looking to 2100, the report anticipated an increase in greenhouse gas emissions by 40%, taking atmospheric concentration to 685 ppm and setting the world up for a 3–6°C temperature increase. That Baseline obviously suggests that many current path trends need to be changed.

Policy suggestions in the OECD's (2012) study targeted specific red light issues. The authors also called for a search for synergies across possible interventions, the use by governments of partnerships with other social actors, and international cooperation. The studies of the red light issues listed, and then discussed at some length, various policies potentially available to address the issues. They then provided alternative projections (sometimes based on other studies) that could be possible depending on, but not precisely linked to, different packages of interventions. The policy scenarios also interacted with varying technological assumptions. Although the policy analysis could be considered a variation of the Policy Reform scenario of the GSG, the intervention-focused analysis approach was quite different from that of an integrated, macro scenario (see the policy analysis discussion later in this chapter).

In addition to whether such policies will materialize, major uncertainties are, of course, on the environmental side itself. For instance, the study pointed out that:

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[3] See OECD, 2012, p. 57 for a description of the conditional convergence methodology used in the study and page 59 of that source regarding the changing sectoral character of economies around the world.

[4] The OECD 2012 report pointed out that the accounting for primary energy related to some electricity sources varies, and that it used the International Energy Agency approach (33% efficiency for nuclear and 100% for renewable sources). As Section 7.2.5 of this volume discussed, the growth of renewable share in the IMAGE current path projection is slow, and the OECD study used IMAGE output (OECD, 2012, p. 61). It also used an annual reduction of 1.3% in energy intensity of the global economy.

> There is compelling scientific evidence that natural systems have "tipping points" or biophysical boundaries beyond which rapid and damaging change becomes irreversible (e.g., for species loss, climate change, groundwater depletion, land and soil degradation). However, these tipping points or thresholds are in many cases not yet fully understood … (OECD, 2012, p. 26)

Further, it directed attention to three different types of uncertainties around model-based projections: parameter values, driver behavior, and model structure. And as the study noted (OECD, 2012, p. 42), "proper validation is a formidable task."

IMAGE-based analysis. In addition to its contributions to the UNEP and OECD studies, the IMAGE system also provided the backbone for a report titled *Roads from Rio + 20* (van Vuuren and Kok, 2012a [full report] and 2012b [summary]). The study, which took place under the auspices of the PBL Netherlands Environmental Assessment Agency, looked back to the 1992 UN Earth Summit meeting in Rio from the vantage point of 20 years later. It concluded that we had failed to achieve the Earth Summit's vision of reaching human development and environmental goals, and explored paths on which the world might move forward.

In particular, the study identified two critical clusters of issues very much like the red light issues of the OECD: "ensuring sufficient food supply while conserving biodiversity," and "ensuring a modern energy access for all while limiting global climate change and air pollution" (van Vuuren and Kok, 2012b, p. 18). The method of study (using IMAGE with GLOBIO, GISMO, and FAIR; see again Section 3.1.3) differed somewhat, however. It presented a Trend scenario without significant policy strengthening. It then used "backcasting" from a set of sustainability goals to outline three different prescriptive paths of transformative action and policy action to obtain those goals by 2050. The backcasting technique is significantly qualitative as well as quantitative. Because the analysts develop and refine goal-driven scenario stories via iterative use of the model, many possible scenarios might meet the goals identified and judgment is involved. The titles of the Rio + 20 paths and excerpted descriptions suggest their core elements (van Vuuren and Kok, 2012b, p. 26):

- *Global Technology Pathway*: "… large-scale, technologically optimal solutions, such as intensive agriculture and a high level of international coordination …"
- *Decentralized Solutions Pathway*: "… such as local energy production, agriculture that is interwoven with natural corridors and national pathways …"
- *Consumption Change Pathway*: "… most notably by limited meat intake per capita, by ambitious efforts to reduce waste in the agricultural production chain, and through the choice of a less energy-intensive lifestyle."

Hence the scenario drivers once again tended to cut across technology, institutions/governance/policy, and human behavior, with variations in environmental condition resulting from those. The only significant feedback from environmental to human systems elaborated in the analysis was to health (van Vuuren and Kok, 2012a, p. 78). However, UNEP's GEO-6 drew upon these three scenarios to explore the implications of global change for attaining some of the environmental outcomes of the SDGs (Moyer and Bohl, 2019).

Shared Socioeconomic Pathways. This volume has referred frequently to another important scenario project, the building of the shared socioeconomic pathways (SSPs) (see especially Section 3.3.2.1 and Fig. 3.2). The narratives for these scenarios map five different futures that frame different levels of challenge in mitigation of, and adaptation to, climate change.

The variables that differentiate them still again cross over "demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources" (O'Neill et al., 2017: Abstract; see also O'Neill et al., 2014). This is reflected in the names of the scenarios: Sustainability, Middle of the Road, Regional Rivalry, Inequality, and Fossil-fueled Development.

The effort to create quantitative support for the SSP scenarios has drawn on a wide range of models to provide projections for key variables in the five scenarios. The Wittgenstein Centre/IIASA population and education model (KC and Lutz, 2017) has provided projections in those two areas. The IIASA economic model (Cuaresma, 2017), the OECD economic model (Dellink et al., 2017), and the Potsdam Institute for Climate Impact Research economic model (Leimbach et al., 2017) have all provided GDP projections. The iPETs model at the National Center for Atmospheric Research (Jiang and O'Neill, 2017) contributed urbanization projections. Several IAMs have provided energy projections, although as of mid-2018 those were only for global regions, not countries.

The availability from the IIASA website of those century-long projection sets for multiple variables across the SSPs is a major contribution to the framing and understanding of alternative world futures.[5] The comparative scenario analyses in earlier chapters of this volume have drawn very heavily on those projection sets to help understand the landscape of scenarios and projections within issue areas and to show how projections from IFs and other models fit into that landscape. We have seen in many of the Comparative Scenario sections of this volume (see, e.g., Sections 6.1.5, 7.1.5, and 7.2.5) how other model projects have also picked up the SSPs to present a range of issue-specific projections.

In addition, Section 3.3.2.1 discussed how the most recent phase of the Coupled Model Intercomparison Project (CMIP) is linking the alternative greenhouse gas accumulations of the Representative Concentration Pathways (RCPs) and the SSPs. That work will strengthen foundations for more fully connecting projections across the human, social, and biophysical systems; as Section 8.1.2 emphasized, the linkages from environmental change to human and social development especially need more attention. Because of the framing of the SSPs in terms of both mitigation and adaptation, the linkages with climate change are inherently two-directional.

9.2.4 Some Strengths and Weaknesses of Much General Framing Scenario Analysis

This overview of major scenario exercises with global models suggests some of their general characteristics. The uncertainties that frame scenarios range across, and very often explicitly link, the three issue domains of this volume, and the scenarios indicate the very wide range of uncertainty within and across those domains. Also, as discussed throughout, there is much commonality in the dimensions of uncertainty that frame scenario sets.

Scenarios also facilitate the addition of prescriptive visions to otherwise empirically rooted analysis. Further, they can help analysis reach beyond the constraints that historical paths tend to create, thereby potentially allowing consideration, for instance, of disruptive

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[5] The SSP projection sets are available at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

technological change. And, as the next section elaborates, they can begin to bridge the gap from framing large uncertainties to exploring the implications of specific policy interventions.

There are inevitably some weaknesses in the scenario building enterprise. In some cases, the effort to fully frame uncertainty can convey numbers that seem unnecessarily extreme (earlier chapters have noted instances). In other cases, current paths can be presented as reference points when their bending is already underway. We have also already noted that models often have issue foci and structures that make the creation of coherent scenario stories across multiple issues difficult. In particular, the focus of most IAMs on the causes of environmental change without elaboration of the impacts of it on human and social systems is a limitation. The global articulation of Sustainable Development Goals (SDGs) and the effort to achieve them have helped make these limitations obvious, and projects like CD-LINKS (see Section 3.3.2.2) have begun to address them.

In short, scenario building and exploration projects are essential in helping us better understand uncertainty. Existing weaknesses can be addressed and progress in doing so is being made.

9.3 CREATING BETTER FUTURES: POLICY ANALYSIS SCENARIOS

Alternative scenarios can help map the range of uncertainty and, to some degree at least, the range of risk and opportunity that we might face in coming years. As in the analysis with them of climate change, they can also point to the broad policy orientations that would be helpful in shaping more desirable futures. However, broad framing scenarios tend to reflect major uncertainties rather than elaborating the more specific human actions that might reduce them. Hence decision makers frequently find it difficult to use them to inform their choices.

As van Vuuren et al. (2012) argued, when general insight and understanding in a field mature, there is a natural progression from broad framing or exploratory scenarios to more policy-oriented analysis.[6] The various *Environmental Outlook* volumes of the OECD illustrate such a focus on policy. As Section 2.5 noted, one might better characterize the study of policy with models as creating interventions or "runs" rather than scenarios. Yet it is also possible simply to see it as a different type of scenario analysis.

Global models have weaknesses that make policy focus challenging. Consider, for instance, the big global push on the SDGs. We know that there are many trade-offs between dollar investments in any one of them (e.g., universal secondary education) and most others (e.g., universal access to improved sanitation). We also know that there are many synergies across achievements in any one (e.g., universal access to safe water) and many others (e.g., low infant and maternal mortality). Global models often tend, however, not to be well

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[6] van Vuuren et al. (2012) distinguished between what they called *explorative scenarios* and *policy scenarios*, and argued that the thrust of scenario analysis has moved toward the latter in part because international environmental analysis has been moving through developmental phases of problem recognition, policy formulation, policy implementation, and control, only the first of which generates explorative work. Their concern is that the movement to policy scenarios risks compromising the attention to more extreme possible variation in futures and thus the robustness of resulting policy prescriptions.

structured for the analysis of trade-offs and synergies in the pursuit of such goals; issue-area coverage and connection may be inadequate and/or representation of the systems that are included may be too coarse for such exploration (van Vuuren et al., 2016). Also, many IAMs are not globally country-specific, complicating analysis of very different starting points, policy environments, and cross-country connections.

The IFs project and other global modeling projects have increasingly overlaid policy analysis on broad explorative or framing scenarios. As a trade-off with the breadth of their issue coverage, however, the models tend to facilitate exploration of *policy orientations* rather than highly specific policy interventions. For instance, analysis with IFs suggests that policy makers achieve benefits for individuals and for society more broadly when they:

- invest in education, health, infrastructure, and R&D for human capacity development in and of itself and as a route to greater economic productivity (but does not tell us whether to spend on classrooms, teachers, or teaching materials).
- reduce corruption, raise revenues without diminishing investment incentives, and be more inclusive and democratic across society so as to enhance governance (but does not help in specifying the means for corruption reduction or the details of revenue enhancement measures).
- use taxes and regulatory measures to shift energy systems from fossil fuels to renewable ones, while investing in new technologies to support that shift as well as more efficient use of energy (but does not tell us whether to use financial incentives or regulation).
- put prices on water usage to make demand sustainable (but does not help us decide whether to use flat rates or ones scaled by usage level or differentiated by type of use).
- encourage healthier diets to diminish meat consumption, grazing land expansion, natural habitat destruction, and species extinction (but fail to help us identify the policy nudges that would best encourage the changes).

With respect to such policy orientation analysis, IFs does have the advantage of its representation of 186 countries and its hard-linkage connection of models across a wide variety of issue areas. In analysis of the SDGs, for instance, one of the contributions that the IFs project has been making is to help identify country-specific, time-profile-sensitive “aggressive but reasonable” policy orientations in pursuit of the SDGs while simultaneously exploring the consequences of pursuit of one or more goals for the achievement of other goals (trade-offs and synergies). Hughes (2013) illustrated such analysis with IFs generally; Turner et al. (2015) explored reasonable goals for African poverty reduction; Dickson et al. (2016) focused on pursuit of the goal for universal secondary education, while simultaneously exploring the implications of action for other goals, such as reduction of poverty and infant mortality; and Moyer and Bohl (2019) addressed the prospects for achieving several human-development oriented SDGs in the face of synergies and trade-offs.

Other IAMs clearly also have capacity for more policy oriented analysis. For example, Section 7.5.6 (see Fig. 7.19) noted the use in UNEP analysis of multiple models to explore the impact of unconditional and conditional pledges with respect to greenhouse gas emissions on the annual level of those emissions (UNEP, 2017, p. 15). Although again the exact policy mix that would best limit those emissions might not emerge from such model use, the analysis can provide great help to policy makers through the setting of targets.

Perhaps it is unfair to ask global models for extensive policy detail across multiple goals. Perhaps they accomplish already what their developers set out to do when they produce broad framing scenarios and general insight on particular policy directions. And given inevitable model limitations, model-based policy analysis should always be only one suggestive input to the policy process. However, a declaration of successful enterprise completion seems very premature. The push from society will always be for more and better policy analysis as well as framing and understanding of alternative futures. And considerably more detailed policy analysis can be done. For example, Kriegler et al. (2018) built 13 climate change scenarios around SSP2 representing quite specific policy targets, including retrofitting buildings for energy efficiency at specific annual rates and increasing electric vehicles as a percentage of vehicle sales. They elaborated each with good practice and net zero emission variations, and they used the interventions to determine how to reach the Paris climate goal of holding global temperature change to less than 2°C. Supplementing basic scientific research for better understanding of our world with better support for decisions and policies remains a frontier of global modeling.

9.4 NEXT STEPS IN GLOBAL MODELING—AND IN THE DEVELOPMENT OF IFs

The effort to build long-term quantitative global analysis systems is now about 50 years old. In the first half-century of effort, modelers have created a remarkable capacity for looking at possible futures across all major issue areas of concern to those seeking to improve those futures for current and future generations. Building on data foundations that have dramatically improved, using computer hardware and software that was hardly even conceptualized in the early years of effort, and learning from each other throughout the process, modelers have created powerful tools and provided insightful analyses. In our base case or current path runs we capture key dynamics that provide remarkably clear (but still inevitably uncertain) pictures of where we seem to be going. In our alternative scenarios we communicate coherent images of possible futures and increasingly support policy analysis.

At the same time, this volume has not shied away from identifying the weaknesses of existing models and the challenges to the enterprise going forward. What are some of the greatest needs, and therefore best opportunities, for global modeling? How should the IFs system develop to help meet those needs and grasp those opportunities? Elements include:

- Creating modeling systems to *more comprehensively represent key dynamics across the global development issues and issue clusters* that we recognize to be highly integrated and interdependent. Although as a field or enterprise we have broken (or at least cracked) many of the silo walls that have long divided traditional academic disciplines, much of our effort continues to reflect problem-specific foci, whether limiting global warming or reducing poverty, when the problems and desired outcomes (such as delivering on the SDG goal and target sets) are themselves tightly interrelated.
    - The push for integrated assessment models has represented the drivers from human systems to environmental damage (and our potential for its mitigation) much better than the impact of that damage back to human development and social change. There is considerable room for improvement in understanding that damage in the context of the vulnerability and resilience of human systems.

  - While many hard-linked, cross-model representations in IFs (including those between human and social development) are more developed than is common in global models, its representation of environmental impacts on other systems is, like that of IAMs more generally, underdeveloped, and the project has not taken full advantage of the strength of its representation of human and social systems.
- Progressively *elaborating our models of subsystems as well as their interrelationships*. Often the gap between modelers and policy makers lies in the specificity (or lack thereof) that we can provide. In the language of the philosophy of science, components must be "fit for the purpose." They could be elaborated as standalone models and/or tailored to connect with models of other issue areas, depending on the analysis questions to which they are applied. They should have strong theoretical and empirical bases and be tested against historical patterns and adapted for changes occurring and anticipated.
  - The in-house elaboration and interlinkage of a wide range of models has inherent limitations as specific models (and even important components within them) become increasingly sophisticated and labor intensive to develop and maintain. We may already be pressing some limits with respect to what policy elaboration can tell us.
  - Another major problem is maintaining progress with large-scale models as original developers move on. The time may have come to set up "plug-and-play" modular systems that will allow the swapping into hard-linked systems of alternative formulations, submodules, and even full issue-specific models. More generally, "plug-and-play" would also facilitate hard-linking of evolving models within and across project teams.
  - IFs already has especially extensive coverage of key issue domains and specific issue areas around human development and social change. Its biophysical systems are, however, considerably less well developed. The project needs to continue to enhance the component models in selected areas where others have moved ahead with more detail and/or sophistication, especially when others have put forward stronger representations more usable in policy analysis. Alternatively, (or in addition), the IFs project could seek ways to selectively connect IFs to more sophisticated models made available by others, particularly with respect to the environment.
  - Two elements of the IFs system already position it well for policy analysis: (1) the representation of government revenues and expenditures by issue area within a social accounting matrix that assures the fiscal consistency important to trade-off analysis and (2) the endogenous representation of multifactor productivity as a function of developments in human, social, physical, and knowledge capital, thereby again treating trade-offs but also synergistic combinations. However, both of these representations require constant enhancement for analysis of the SDGs and more general policy analysis support.
- *Making the systems we build more transparent and open* not just to other scientists and model builders (a minimal requirement) but ideally to the policy and lay communities that we seek to inform and assist. Too often our tools have been not only inaccessible to those broader communities but unavailable for close examination and use by our modeling colleagues.
  - Wiki documentation systems, like that of the Integrated Assessment Modeling Consortium that grew from the ADVANCE project, have begun to help with this. Documentation updates, however, lag too far behind model development and are often

  incomplete or superficial. Some projects have begun using GitHub not only to share documentation but also code.
  - IFs has been available for others to use on their own computers for all of its development history, and it has been available for on-web use since 2001. Further, the code of IFs, both equations and algorithms, is extensively documented by model (albeit frequently with too much lag), and that code is under general public license for others to use. The need for supportive software systems has, however, greatly limited use by others.
  - The graphical user interface (GUI) of IFs allows complete access to the system, has attracted a wide and steadily increasing range of users, and generates regular feedback from those users that helps drive both interface and model enhancements. Still, that GUI also requires movement up a learning curve, in large part because the system is so extensive (it provides full access to and analytical use of data, allows extensive basic and specialized display and analyses of Base Case and other scenarios, and facilitates creation, saving, and extension of scenarios). The GUI needs to undergo transformations to be congruent with the state of the art for web-based systems and to keep pace as that art continues its rapid progression.
- *Understanding more fully the uncertainties around our looking ahead and reducing those*, including the limitations of our model structures and formulations generally, but with special attention to treatment of ongoing and future disruptive forces including (and beyond) climate change. Model projects will reduce uncertainties when possible, but need to lay them out clearly when not. While climate change and other environmental damage associated with human activities must and will continue to require a significant portion of the attention of global modelers, other disruptive forces may increasingly shape the challenges and opportunities of the 21st century. Among the most important are technological advance with respect to (a) artificial intelligence and robotics and (b) biomedical understanding, with associated longevity extension. The challenges to humanity of changing employment opportunities with associated impact on inequality and of growing elderly populations with or without good health will potentially grow relative to, and in interaction with, that of environmental sustainability.
  - With respect to climate change and other environmental issues, both model intercomparison efforts and scenario building are helping with mapping uncertainty. However, model intercomparisons have sometimes given us more information about a range of projections across models than the reasons for their differences, and scenario comparison has sometimes rather formalistically mapped a range of variation with inadequate exploration of the foundations of differences.
  - Although the IFs project has begun to develop its capabilities for exploring a wide range of disruptive forces with uncertain impacts (including not only climate change but also AI/robotics, life extension, and global power transition), it needs to extend its capabilities for addressing emerging and potential global challenges.
  - The IFs project has been extremely active in scenario development. It has replicated scenarios from many scenario analysis projects and built a large library of interventions that can be used individually and in combination via its interface. These include the UNEP GEO-4 scenarios as a pre-run set accompanying the model in the downloadable version and many dozens pre-run in the web-based version. Moreover, the IFs project

has worked with nongovernmental organizations, intergovernmental organizations, provinces, countries, and companies around increasingly concrete and policy-linked questions. As a result, however, IFs scenario intervention files have proliferated, and differences are not always transparent to users.

On a personal closing note, I admit to feeling uncomfortable concerning any prediction of the future, including that for global, integrated, and long-term models. However, in spite of the focus of this chapter heavily on what we have yet to do, I believe that the global modeling community has greatly helped make it possible to understand our world—including where it is going and how positively to bend the curves of change toward reaching global goals—incredibly much better than was possible 50 years ago. And I express my confidence that the advances over the coming decades will amaze an analyst of them as much as those of the last half century impress me today.

References

Cuaresma, J.C., 2017. Income projections for climate change research: a framework based on human capital dynamics. Glob. Environ. Chang. 42 (January), 226–236. https://dx.doi.org/10.1016/j.gloenvcha.2015.02.012.

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the shared socioeconomic pathways. Glob. Environ. Chang. 42 (January), 200–214. https://dx.doi.org/10.1016/j.gloenvcha.2015.06.004.

Diamond, J., 2005. Collapse: How Societies Choose to Fail or Succeed. Viking Press, New York, NY.

Dickson, J.R., Irfan, M.T., Hughes, B.B., 2016. USE 2030: Exploring Impacts, Costs, and Financing. Background Paper provided by the Frederick S. Pardee Center for International Futures for the International Commission on Financing Global Education Opportunity report, The Learning Generation. International Commission on Financing Global Education Opportunity, New York, NY. http://report.educationcommission.org/wp-content/uploads/2016/11/USE-2030-Exploring-Impacts-Costs-and-Financing.pdf.

Gallopín, G., Al, H., Raskin, P., Swart, R., 1997. Branch Points: Global Scenarios and Human Choice. PoleStar Series Report no. 7. Stockholm Environment Institute, Stockholm, Sweden. http://www.tellus.org/pub/Branch%20Points%20-%20Global%20Scenarios%20and%20Human%20Choice.pdf.

Gidley, J.M., 2017. The Future: A Very Short Introduction. Oxford University Press, Oxford, UK.

Hughes, B.B. (Ed.), 2013. Development-Oriented Policies and Alternative Human Development Paths: Aggressive but Reasonable Interventions. Prepared by the Frederick S. Pardee Center for International Futures. UNDP Occasional Paper 2013/05. Human Development Report Office, United Nations Development Programme, New York, NY. http://hdr.undp.org/sites/default/files/hdro_1305_pardee.pdf.

Jiang, L., O'Neill, B.C., 2017. Global urbanization projections for the shared socioeconomic pathways. Glob. Environ. Chang. 42 (January), 193–199. https://dx.doi.org/10.1016/j.gloenvcha.2015.03.008.

KC, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Chang. 42 (January), 181–192. https://dx.doi.org/10.1016/j.gloenvcha.2014.06.004.

Kriegler, E., Bertram, C., Kuramochi, T., Jakob, M., Pehl, M., Stevanovic, M., et al., 2018. Short term policies to keep the door open for Paris climate goals. Environ. Res. Lett. 13(7): 074022. https://dx.doi.org/10.1088/1748-9326/aac4f1.

Leimbach, M., Kriegler, E., Roming, N., Schwanitz, J., 2017. Future growth patterns of world regions—a GDP scenario approach. Glob. Environ. Chang. 42 (January), 215–225. https://dx.doi.org/10.1016/j.gloenvcha.2015.02.005.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. U. S. A. 105 (6), 1786–1793.

Lomborg, B. (Ed.), 2013. How Much Have Global Problems Cost the World: A Scorecard From 1900 to 2050. Cambridge University Press, Cambridge, UK.

Meadows, D.L., Behrens III, W.W., Meadows, D.H., Naill, R.F., Randers, J., Zahn, E.K.O., 1974. Dynamics of Growth in a Finite World. Wright-Allen Press, Cambridge, MA.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC. http://www.millenniumassessment.org/documents/document.356.aspx.pdf.

Miller, R. (Ed.), 2018. Transforming the Future: Anticipation in the 21st Century. Routledge, New York, NY.

Moyer, J.D., Bohl, D., 2019. Alternative pathways to human development: Assessing trade-offs and synergies in achieving the Sustainable Development Goals. Futures 105 (January), 199–210. https://dx.doi.org/10.1016/j.futures.2018.10.007.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., et al., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Chang. 122 (3), 387–400. https://dx.doi.org/10.1007/s10584-013-0905-2.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., et al., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42 (January), 169–180. https://dx.doi.org/10.1016/j.gloenvcha.2015.01.004.

Organisation for Economic Co-operation and Development (OECD), 2008. OECD Environmental Outlook to 2030. OECD Publishing, Paris, France. https://dx.doi.org/10.1787/9789264040519-en.

Organisation for Economic Co-operation and Development (OECD), 2012. OECD Environmental Outlook to 2050: The Consequences of Inaction. OECD Publishing, Paris, France. https://dx.doi.org/10.1787/9789264122246-en.

Pinker, S., 2011. The Better Angels of Our Nature: Why Violence Has Declined. Viking Books, New York, NY.

Pinker, S., 2018. Enlightenment Now: The Case for Reason, Science, Humanism, and Progress. Viking Books, New York, NY.

Poli, R., 2010. An introduction to the ontology of anticipation. Futures 42 (7), 769–776. https://dx.doi.org/10.1016/j.futures.2010.04.028.

Raskin, P., Gallopín, G., Gutman, P., Al, H., Swart, R., 1998. Bending the Curve: Toward Global Sustainability. PoleStar Series Report no. 8. Stockholm Environment Institute (U.S. Center) and Tellus Institute, Boston, MA. http://www.tellus.org/pub/Bending%20the%20Curve%20-%20Toward%20Global%20Sustainability.pdf.

Raskin, P., Banuri, T., Gallopín, G., Gutman, P., Al, H., Kates, R., Swart, R., 2002. Great Transition: The Promise and Lure of the Times Ahead. PoleStar Series Report no. 10. Stockholm Environment Institute (U.S. Center) and Tellus Institute, Boston, MA. http://www.greattransition.org/documents/Great_Transition.pdf.

Raskin, P.D., Electris, C., Rosen, R.A., 2010. The century ahead: searching for sustainability. Sustainability 2 (8), 2626–2651. https://dx.doi.org/10.3390/su2082626.

Ridley, M., 2011. The Rational Optimist: How Prosperity Evolves. HarperCollins, New York, NY.

Rothman, D.S., Agard, J., Alcamo, J., 2007. The future today. In: United Nations Environment Programme, Global Environment Outlook 4 (GEO 4): Outlook for Development. United Nations Environment Programme, Nairobi, Kenya, pp. 397–456.

Simon, J., 1981. The Ultimate Resource. Princeton University Press, Princeton, NJ.

Toynbee, A.J., 1934–1961. A Study of History, 12 volumes. Oxford University Press, Oxford, UK.

Turner, S., Cilliers, J., Hughes, B., 2015. Reasonable Goals for Reducing Poverty in Africa: Targets for the Post-2015 MDGs and Agenda 2063. Africa Futures Paper 13. Institute for Security Studies and Frederick S. Pardee Center for International Futures, Pretoria, South Africa; Denver, CO.

United Nations Environment Programme (UNEP), 2017. The Emissions Gap Report 2017. United Nations Environment Programme, Nairobi, Kenya. https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf.

van Vuuren, D.P., Kok, M. (Eds.), 2012a. Roads from Rio+20: Pathways to Achieve Global Sustainability Goals by 2050. Full Report. PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands. http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2012-roads-from-rio-pathways-to-achieve-global-sustainability-goals-by-2050.pdf.

van Vuuren, D.P., Kok, M. (Eds.), 2012b. Roads From Rio + 20: Pathways to Achieve Global Sustainability Goals by 2050. Summary and Main Findings to the Full Report. PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands. http://www.pbl.nl/sites/default/files/cms/publicaties/PBL_2012_Roads%20from%20Rio_500062001.pdf.

van Vuuren, D.P., Kok, M.T.J., Girod, B., Lucas, P.L., de Vries, B., 2012. Scenarios in global environmental assessments: key characteristics and lessons for future use. Glob. Environ. Chang. 22 (4), 884–895. https://dx.doi.org/10.1016/j.gloenvcha.2012.06.001.

van Vuuren, D.P., Lucas, P.L., Häyhä, T., Cornell, S.E., Stafford-Smith, M., 2016. Horses for courses: analytical tools to explore planetary boundaries. Earth Syst. Dynam. 7 (1), 267–279. https://dx.doi.org/10.5194/esd-7-267-2016.

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INTERNATIONAL FUTURES

Building and Using Global Models

BARRY B. HUGHES

Global modeling – the creation of computer systems for long-term, integrated study of multiple issues – has progressed steadily across half a century. Increasingly clear definition of global problems, including climate change, and commitment to global initiatives, including the Sustainable Development Goals (SDGs), motivate ongoing model advance.

This volume uniquely reviews the overall status of global modeling, devoting special attention to the International Futures (IFs) system. IFs integrates models across the issue domains of human development (demography, education, and health), social change (economics and governance), and environmental sustainability (the impacts of agriculture, energy, and infrastructure on water use and climate). The volume explains global modeling, sketches issue-specific global transitions, elaborates conceptual and theoretical understandings of change, explores a wide range of models, details the IFs approach, and compares projections of IFs and other models.

A special modeling challenge is representation of relationships across issues, including the complicated interaction of positive developments in human development with growing damage to the environment. Understanding the trade-offs and synergies associated with simultaneous pursuit of multiple SDGs poses a related challenge. The volume explores the building of such issue linkages, the potential for model use in policy analysis, and the use of scenarios to address uncertainties.

Barry Hughes has developed global models for 40 years. He was the founding director of the Frederick S. Pardee Center for International Futures at the University of Denver's Josef Korbel School of International Studies, and supports continued progress of IFs and its open use by policy analysts, modelers, scholars, and all others interested in improving global futures.

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