Chapter 8
Integrated Assessment Modeling

James A. Edmonds, Katherine V. Calvin, Leon E. Clarke, Anthony C. Janetos, Son H. Kim, Marshall A. Wise, and Haewon C. McJeon

Glossary

Climate policy (greenhouse gas mitigation policy)	A climate policy refers to a policy scheme designed to deliberately limit the magnitude of climate change, often involving mitigation of greenhouse gases. Integrated assessment models (IAMs) represent climate policies in abstract forms. The most commonly modeled climate policy is attaching a universal price on emissions of carbon dioxide (or carbon dioxide equivalent of other greenhouse gases). Such policy represents a universal carbon tax or an economy-wide cap-and-trade policy. Other forms of climate policies, such as differential carbon price by sector or renewable portfolio standards, have also been used in IAMs.
Cost of greenhouse gas mitigation (economic cost)	Integrated assessment models (IAMs) employ varies metrics for estimating the economic cost of mitigation policy. One common approach estimates reduction in GDP, a proxy for slowdown in economic activity due to increased price of energy and agricultural products. Another approach estimates the (gross) loss in social welfare due to a policy by measuring the area under the marginal abatement cost

| | curve. Other metrics include foregone consumption, compensated variation, and equivalent variation. |
Integrated assessment model (IAM)	Integrated assessment model (IAM) in climate change research is a model which simulates the interactions of human decision-making about energy systems and land use with biogeochemistry and the natural Earth system. IAMs can be divided into two categories.
	Higher resolution IAMs focus on explicitly representing processes and process interactions among human and natural Earth systems.
	Highly aggregated IAMs use highly reduced-form representations of the link between human activities, impacts from climate change, and the cost of emissions mitigation.
Integrated earth system model (iESM)	Integrated Earth System Models (iESMs) are a class of models under development by collaboration between integrated assessment modeling community and climate modeling community. By fully integrating the human dimension from an IAM and the natural dimension from a climate model, iESM allows simultaneously estimating human system impacts on climate change and climate change impacts on human systems, as well as examining the effects of feedbacks between the components.
Land use (land-use emissions)	Land use is one of the largest anthropogenic sources of emissions of greenhouse gases, aerosols, and short-lived species. Emissions, as well as sequestration of emissions, may occur from land-use practices, changes in land cover, or changes in forested area or the density. On the other hand, land-use patterns are affected by the changes in the climate. As such, modeling land use has been an important component of the integrated assessment modeling of climate change.
Representative concentration pathways (RCPs)	The Representative Concentration Pathways (RCPs) are the most recent set of emission scenarios generated by integrated assessment models. Four scenarios explicitly considering emission mitigation efforts that were sufficiently differentiated in terms of radiative forcing at the end of the century were selected from published literature. RCPs are designed to facilitate the interactions with climate models by including geospatially resolved emissions and land-use data.

Definition of the Subject

This entry discusses the role of integrated assessment models (IAMs) in climate change research. IAMs are an interdisciplinary research platform, which constitutes a consistent scientific framework in which the large-scale interactions between

human and natural Earth systems can be examined. In so doing, IAMs provide insights that would otherwise be unavailable from traditional single-discipline research. By providing a broader view of the issue, IAMs constitute an important tool for decision support. IAMs are also a home of human Earth system research and provide natural Earth system scientists information about the nature of human intervention in global biogeophysical and geochemical processes.

Introduction

Integrated assessment models (IAMs) are a class of models which simulate the interactions of human decision-making about energy systems and land use with biogeochemistry and the natural Earth system (see Fig. 8.1). In so doing, IAMs provide insights that would otherwise be unavailable from investigating either
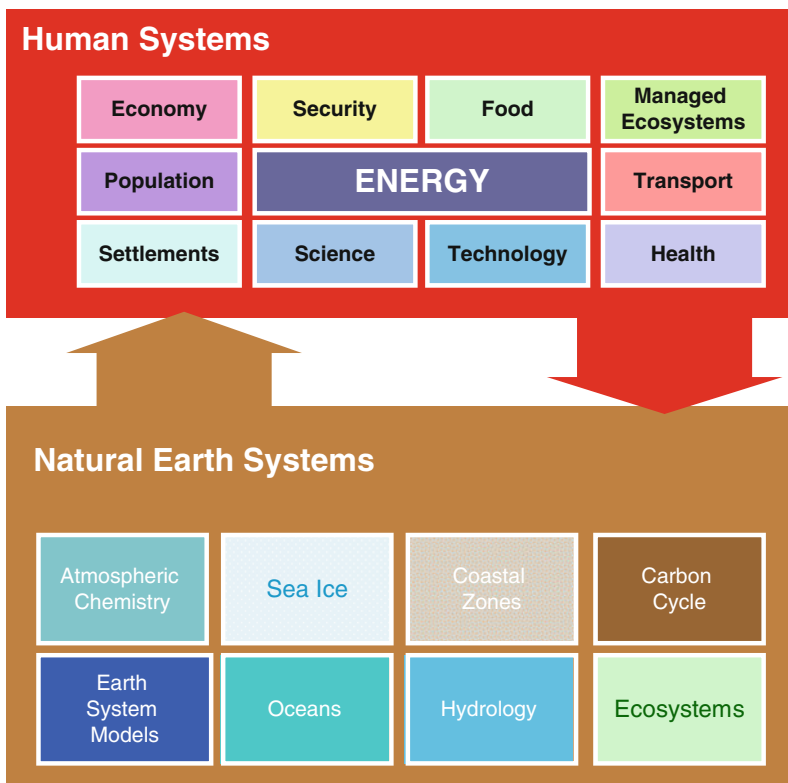
Fig. 8.1 Integrated assessment models integrate human and physical Earth system climate science (Source: Janetos et al. [72])

natural systems or human systems, or their various components, alone. By their nature, IAMs capture interactions between complex and highly nonlinear systems. IAMs serve multiple purposes. One purpose is to provide natural science researchers with information about human systems such as greenhouse gas emissions, land use, and land cover. Another purpose of IAMs is to help human system researchers – such as social scientists – better understand the nature of the human impacts on the natural Earth systems.

Traditionally, researchers have relied on models that are each built on the foundations of a single discipline – such as economics, geography, meteorology, etc. By integrating research methods from various disciplines that characterize both the human and natural Earth systems, IAMs produce insights that would not otherwise be available from disciplinary research. The work of Wigley, Richels, and Edmonds [1] provides a classic example of the nature of insights that are available from the explicit linking of human and Earth systems. Wigley et al. showed that the consideration of economic efficiency in the context of the physical carbon cycle carried important implications for the timing of emissions and emissions mitigation in a world seeking to stabilize the concentration of atmospheric CO_2. In other words, the imposition of human system considerations – in this case economic efficiency considerations – led to a different and smaller set of emissions pathways for consideration than were indicated by Earth system considerations alone.

This entry discusses a range of selected topics associated with the development and use of IAMs. This is not an extensive survey of the literature and the available models. Instead, it focuses on a selected set of topics required to understand the various types and uses of IAMs as well as those required to understand the direction of cutting-edge IAM research. In addition, the entry focuses more heavily on the strain of IAMs and integrated assessment modeling (IA modeling) research focused on more effectively modeling human and Earth system processes (higher resolution IAMs) than on the strain of IAMs and IA modeling research that focuses on more aggregate representations of these systems to allow for cost-benefit analysis. The remainder of this entry proceeds as follows. Section "The Variety of Integrated Assessment Models" focuses on the emerging distinction between highly aggregated and higher resolution IAMs. Section "GCAM as an Example of a Higher Resolution IAM" then follows with a discussion of the Global Change Assessment Model (GCAM) as an example of a higher resolution IAM. Section "Using Higher Resolution IAMs to Analyze the Impact of Policies to Mitigate Greenhouse Gas Emissions" discusses the long history of using IAMs to explore the costs of greenhouse gas policies as well as several of the most important conceptual issues that the IAMs have had to wrestle with in this regard. Section "Future Directions: Integrating Climate Impacts with IAM" then explores an important cutting-edge research direction for higher resolution IAMs: the inclusion of structural or process models of climate impacts.

The Variety of Integrated Assessment Models

There are many approaches that have been used to develop and use IAMs. Indeed, every IAM is different. One of the most important ways that IAMs are distinguished from one another is the level of resolution at which they model the underlying human and natural Earth system process. At one end of the spectrum are *highly aggregated* IAMs. Highly aggregated IAMs use highly reduced-form representations of the link between human activities, impacts from climate change, and the cost of emissions mitigation. At the other end of the spectrum are *higher resolution* IAMs. Higher resolution IAMs focus on explicitly representing processes and process interactions among human and natural Earth systems. The following two subsections provide background on each of these two classes of IAMs.

Highly Aggregated IAMs

The highly aggregated class of IAMs was developed to be able to explore the general shape of optimal climate policy, taking into account both the economic costs of mitigation and the economic damages from a changing climate. Highly aggregated IAMs typically frame the climate change mitigation problem in a cost-benefit framework, choosing emission pathways by explicitly weighing the economic costs of mitigation with the economic benefits of reduced impacts. For this reason, highly aggregated IAMs often focus on issues such as the social cost of carbon or optimal tradeoffs over time between mitigation and impacts. Simplicity and parsimony are main virtues of highly aggregated IAMs.

The oldest of the highly aggregated IAMs is the DICE (Dynamic Integrated model of Climate and the Economy) model, whose antecedents have roots in the work of Nordhaus and Yohe [2]. The original DICE model [3] was utilized to explore the integration of human and natural Earth systems as part of a cost-benefit calculation. Originally developed as a one-region global model, DICE was soon followed by a multiregional version, RICE (Regional dynamic Integrated model of Climate and the Economy) [4]. Other such models also emerged building on the Nordhaus-Yohe and DICE paradigm of combining economic costs and benefits in a single framework. These models include, among others, ICAM (the Integrated Climate Assessment Model) [5], PAGE (Policy Analysis of the Greenhouse Effect) [6], and FUND (Climate Framework for Uncertainty, Negotiation and Distribution) [7] (Weyant et al. [8] and Parson and Fisher-Vanden [9] provide good sources of information on pioneering IAMs).

Highly aggregated IAMs are generally composed of three parts: emissions and mitigation, atmosphere and climate, and climate impacts. Mitigation cost and climate change damages are typically monetized (i.e., expressed in dollars or another currency) to allow comparison between mitigation and impacts on a common basis. Highly aggregated IAMs do not attempt to describe in detail either

the energy system or the land-use systems that generate emissions. Similarly, detailed descriptions of the physical process links between climate change and emissions are generally beyond their scope. Instead these models use emissions mitigation supply schedules and climate damage functions. The former maps the relationship between the degree of emissions mitigation and associated cost, while the latter represents the relationship between a measure of climate change and the economic value of damages including both damages from market and nonmarket activities. The strength of these reduced-form representations is that they allow highly aggregated IAMs to weigh costs and benefits explicitly. The drawback is that they cannot provide insight into the actual processes that lead to these costs and benefits.

The technical structure of highly aggregated models is simple, but the equations and associated parameterizations are carefully estimated to capture the behavior of more complex systems. These functions are parameterized by either approximating the behavior of more complex process models, or by fitting simple equations to highly aggregated variables. Analyses using FUND, for example, often produce simple equations that capture the behavior of systems that are represented in more complex models and data. Some models use a simpler approach, in which the economic damages from a prescribed level of climate change are first estimated – for example, a 2°C global mean surface temperature change (GMST) relative to preindustrial level – and a simple function that passes through the estimate – for example, a power function – is assigned to represent the relationship between GMST and total economic damages.

A principle role of highly aggregated IAMs is to integrate and to compare in a common metric, both mitigation effort and climate change impact – each estimated from different disciplines – in order to determine the optimal pathway of emissions reductions or the social cost of carbon. Valuation of damages provides substantial conceptual challenges for highly aggregated IAMs. For example, they must put a value on the loss of human lives as well as nonmarket damages. Another difficult challenge faced by highly aggregated IAMs concerns the relative valuation of impacts that occur at different points in time. See Box 8.1 for details.

Other issues that arise within the highly aggregated IAM paradigm include the problem of interactive effects, that is, the state of one system directly affects the state of another. For example, emissions mitigation may have large-scale effects on land use, which in turn affect the climate, or the climate system may change as a consequence of land-use policy. A challenge for highly aggregated IAMs is to represent such complex interactions in a simple model structure.

Another challenge for highly aggregated IAMs is to determine how to treat impacts occurring outside of the country undertaking the valuation. Early work with highly aggregated IAMs looked at the problem of climate change from the perspective of a single, global, infinitely lived decision maker. But, more recent work has shifted from the perspective of the globe (e.g., [3, 11]) to the perspective of a single country, for example, the United States [14].

Box 8.1. Valuation over Time and Across Generations

Climate change is an issue that is inherently long term as well as global. The nature of carbon cycle processes and their associated time scales create a cumulative relationship between CO_2 emissions and concentrations in the atmosphere (and ocean). Thus, unlike traditional atmospheric pollution problems, control of emissions to a level is insufficient to control the concentration of greenhouses in the atmosphere. In other words, CO_2 and other greenhouse gases are stock pollutants.

One of the most important determinants of the social cost of carbon is the rate at which future events are discounted back to the present. Nordhaus [10] argues that the order of magnitude difference between his estimate of the social value of carbon, derived using DICE, and the value estimated in the Stern Report [11], derived using PAGE, is predominantly a result of the differences in valuing the present relative to the future.

The problem is that there is no consensus on precisely how to approach discounting over periods of time long enough to connect multiple generations. The issues are laid out in Portney and Weyant [12], where the editors note in their overview chapter that "those looking for guidance on the choice of a discount rate could find justification for a rate at or near zero, as high as 20% and any and all values in between" ([12], p. 4). The range of estimates for the appropriate discount rate is generally nonnegative, though even that generalization has its exceptions, for example [13].

Methods for determining the appropriate method for discounting the future can be grouped into two general categories – those which are *prescriptive* and those which are *descriptive*. The prescriptive approach appeals to ethical and moral grounds for choosing a discount rate, while the descriptive approach appeals to observed rates of return on assets in economic markets. It is frequently observed that prescriptive approaches tend to generate lower discount rates than descriptive approaches.

The Higher Resolution IAMs

The higher resolution IAMs have roots in the same era as the highly aggregated IAMs. However, they were developed along different lines to serve different purposes. The higher resolution IAMs were developed to provide detailed information about human and natural Earth system processes and the interactions between these processes. The initial focus of these models was the determinants of anthropogenic carbon emissions. To address this problem, IAMs developed detailed representations of the key features determining long-term energy production, transformation, and end use. The higher

Table 8.1 Some higher resolution integrated assessment models

Some higher resolution integrated assessment models with interdisciplinary research teams		
Model	Home institution	Web link
AIM Asia-Pacific integrated model	National Institutes for Environmental Studies, Tsukuba, Japan	http://www-iam.nies.go.jp/aim/
GCAM Global change assessment model	Joint Global Change Research Institute, PNNL, College Park, MD	http://www.globalchange.umd.edu/models/gcam/
IGSM Integrated global system model	Joint Program on the Science and Policy of Global Change, MIT, Cambridge, MA	http://globalchange.mit.edu/igsm/
IMAGE The integrated model to assess the global environment	PBL Netherlands Environmental Assessment Agency, Bildhoven, The Netherlands	http://themasites.pbl.nl/en/themasites/image/
MERGE Model for evaluating the regional and global effects of GHG reduction policies	Electric Power Research Institute, Palo Alto, CA	http://www.stanford.edu/group/MERGE/
MESSAGE Model for energy supply strategy alternatives and their general environmental impact	International Institute for Applied Systems Analysis; Laxenburg, Austria	http://www.iiasa.ac.at/Research/ENE/model/message.html
ReMIND Refined model of investments and technological development	Potsdam Institute for Climate Impact Research; Potsdam, Germany	http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/

resolution models distinguished different forms of energy, their supplies, demands, and their transformation from primary energy to fuels and electricity for use in end-use sectors such as buildings, transportation, and industry. Examples of higher resolution IAMs are provided in Table 8.1.

Over time these models have grown in complexity. The models have added increasing detail to their representations of both the energy system and the economy. They also broadened their scope, adding natural Earth system processes such as carbon cycle. The current generations of higher resolution IAMs also typically contain representations of agriculture, land use, land cover, and terrestrial carbon cycle processes in addition to representations of atmosphere and climate processes. While all of the higher resolution IAMs model both human and natural Earth system processes, each model was developed independently and each IAM development path emphasized different features of the climate change problem. Some emphasized the development of detailed atmosphere and climate system models. Some focused on detailed representations of technology. Others focused on regional differences in emission patterns and energy systems data. The complex nature of the models requires interdisciplinary research and modeling teams, some of which are listed in Table 8.1.

Because the higher resolution IAMs have grown in their complexity over time, describing the structure of each model in detail is beyond the scope of this entry. For a reference, comparison of three IAMs – IGCM, MERGE, and MiniCAM (the direct ancestor of GCAM) – can be found in [14]. Here, we present the summary comparison table from the report in Table 8.2. All three of these modeling systems have evolved considerably in the subsequent years.

GCAM as an Example of a Higher Resolution IAM

Introduction to GCAM

Rather than try to describe and compare the set of higher resolution IAMs, we have chosen to describe here the Global Change Assessment Model (GCAM) as an example of the higher resolution IAM genre. GCAM is the oldest of the higher resolution IAMs. It traces its roots to work initiated in the late 1970s. The model's first applications were completed in the early 1980s by Edmonds and Reilly [15–18]. Over time the model has developed and evolved through a series of advances documented in a variety of papers including [19–22]. Documentation for GCAM under its previous name, MiniCAM, can be found at http://www.globalchange.umd.edu/models/MiniCAM.pdf/. Other higher resolution IAMs, such as IMAGE and MESSAGE, also use MAGICC to represent atmosphere and climate processes.

At the top level the GCAM model is broken into two interacting system, human Earth system and natural Earth systems. Each of these systems in turn is made up of subsystems. This is the basic structure of all IAMs. GCAM and the other higher resolution IAMs are distinguished from the highly aggregated IAMs in the degree of detail that is incorporated in describing human and natural Earth systems.

All higher resolution IAMs emphasize the representation of human activities and their connection to the sources of greenhouse gas emissions. However, each modeling team has taken a different approach. For example, the IGSM employs a computable general equilibrium (CGE) model of the economy [23]. CGE models emphasize the structure of the economy and the interaction of economic sectors with each other and with labor and capital markets. The MERGE model also employs a highly aggregated CGE model in combination with more highly disaggregated energy sector models all embedded in an intertemporal optimization framework [24, 25]. The Asia-Pacific Integrated Model (AIM) employs a set of models that are used in combination [26]. The GCAM model uses a partial equilibrium framework, rather than a CGE framework. Partial equilibrium models delve into more detail in sectors that are directly related to the analysis in question (e.g., energy supply and demand, agricultural production, land use, and land-use change), and treat other sectors of the economy in aggregate.

Table 8.2 Characteristics of the three integrated assessment models

Feature	IGSM (with EPPA economics component)	MERGE	MiniCAM
Regions	16	9	14
Time horizon, time steps	2100, 5-year steps	2200, 10-year steps	2095, 15-year steps
Model structure	General equilibrium	General equilibrium	Partial equilibrium
Solution	Recursive dynamic	Inter-temporal optimization	Recursive dynamic
Final energy demand sectors in each region	Households, private transportation, commercial transportation, service sector, agriculture, energy-intensive industries, and other industry	A single, nonenergy production sector	Buildings, transportation, and industry (including agriculture)
Capital turnover	Five vintages of capital with a depreciation rate	A putty clay approach wherein the input-output coefficients for each cohort are optimally adjusted to the future trajectory of prices at the time of investment	Vintages with constant depreciation rate for all electricity-sector capital; capital structure not explicitly modeled in other sectors
Goods in international trade	All energy and nonenergy goods as well as emissions permits	Energy, energy-intensive industry goods, emissions permits, and representative tradable goods	Oil, coal, natural gas, biomass, agricultural goods, and emissions permits
Emissions	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, CO, NOx, SOx, NMVOCs, BC, OC, NH_3	CO_2, CH_4, N_2O, long-lived F-gases, short-lived F-gases, and SOx	CO_2, CH_4, N_2O, CO, NOx, SO_2, NMVOCs, BC, OC, HFC245fa, HFC134a, HFC125, HFC143a, SF_6, C_2F_6, and CF_4
Land use	Agriculture (crops, livestock, and forests), biomass land use, and land use for wind and/or solar energy	Reduced-form emissions from land use; no explicit land-use sector; assume no net terrestrial emissions of CO_2	Agriculture (crops, pasture, and forests) as well as biomass land use and unmanaged land; the agriculture-land-use module directly determines land-use change emissions and terrestrial carbon stocks

(continued)

Table 8.2 (continued)

Feature	IGSM (with EPPA economics component)	MERGE	MiniCAM
Population	Exogenous	Exogenous	Exogenous
GDP growth	Exogenous productivity growth assumptions for labor, energy, and land; exogenous labor force growth determined from population growth; endogenous capital growth through savings and investment	Exogenous productivity growth assumptions for labor and energy; exogenous labor force growth determined from population growth; endogenous capital growth through savings and investment	Exogenous productivity growth assumptions for labor; exogenous labor force growth based on population demographics
Energy efficiency change	Exogenous	Proportional to the rate of GDP growth in each region	Exogenous
Energy resources	Oil (including tar sands), shale oil, gas, coal, wind and/or solar, land (biomass), hydro, and nuclear fuel	Conventional oil, unconventional oil (coal-based synthetics, tar sands, and shale oil), gas, coal, wind, solar, biomass, hydro, and nuclear fuel	Conventional oil, unconventional oil (including tar sands and shale oil), gas, coal, wind, solar, biomass (waste and/or residues and crops), hydro, and nuclear fuel (uranium and thorium); includes a full representation of the nuclear fuel cycle
Electricity technologies	Conventional fossil (coal, gas, and oil), nuclear, hydro, natural gas combined cycle (NGCC) with and without capture, integrated coal gasification with capture, and wind and/or solar, biomass	Conventional fossil (coal, gas, and oil), nuclear, hydro, new coal and gas with and without CCS, other renewables	Conventional fossil (coal, gas, and oil) with and without capture; IGCCs with and without capture; NGCC with and without capture; Gen II, III, and IV reactors and associated fuel cycles; hydro, wind, solar, and biomass (traditional and modern commercial)

(continued)

Table 8.2 (continued)

Feature	IGSM (with EPPA economics component)	MERGE	MiniCAM
Conversion technologies	Oil refining, coal gasification, and bio-liquids	Oil refining, coal gasification and liquefaction, bio-liquids, and electrolysis	Oil refining, natural gas processing, natural gas to liquids conversion, coal, and biomass conversion to synthetic liquids and gases; hydrogen production using liquids, natural gas, coal, biomass; and electrolysis, including direct production from wind and solar, and nuclear thermal conversion
Atmosphere – ocean	2-dimensional atmosphere with a 3-dimensional ocean general circulation model, resolved at 20 minute time steps, 4° latitude, 4 surface types, and 12 vertical layers in the atmosphere	Parameterized ocean thermal lag	Global multi-box energy balance model with upwelling-diffusion ocean heat transport
Carbon cycle	Biogeochemical models of terrestrial and ocean processes; depends on climate and/or atmospheric conditions with 35 terrestrial ecosystem types	Convolution ocean carbon cycle model assuming a neutral biosphere	Globally balanced carbon cycle with separate ocean and terrestrial components, with terrestrial response to land-use changes
Natural emissions	CH_4, N_2O, and weather and/or climate dependent as part of biogeochemical process models	Fixed natural emissions over time	Fixed natural emissions over time
Atmospheric fate of GHGs, pollutants	Process models of atmospheric chemistry resolved for urban and background conditions	Single box models with fixed decay rates. No consideration of reactive gases	Reduced-form models for reactive gases and their interactions
Radiation code	Radiation code accounting for all significant GHGs and aerosols	Reduced form, top-of-the-atmosphere forcing	Reduced form and top-of-the-atmosphere forcing; including indirect forcing effects

Source: Clarke et al. [14]

The GCAM model drives the scale of human activities for each of its 14 geopolitical regions utilizing assumptions about future labor force – determined by working-age population, labor participation, and unemployment rate assumptions – along with the assumptions about labor productivity growth. The highly disaggregated energy, agriculture, and land-use components of GCAM are driven by the scale of human activity. The GCAM geopolitical regions are explicitly linked through international trade in energy commodities, agricultural and forest products, and other goods such as emissions permits.

The human dimension of the Earth system as shown in Fig. 8.2 integrates the energy system and the agriculture and land-use system, as well as the economic system that drives the activity in both systems. An important feature of the GCAM architecture is that the GCAM terrestrial carbon cycle model is embedded within the agriculture-land-use system model; that is, the agriculture-land-use system model explicitly calculates net land-use-change emissions from changes in land-use patterns over time. The energy system model produces and transforms energy for use in three end-use sectors: buildings, industry, and transport. The global human Earth systems are modeled for 14 geopolitical regions.

GCAM is a dynamic-recursive market equilibrium model. In each period of time the model's solution algorithm reconciles the supplies and demands for goods and services in all markets by finding a set of market-clearing prices. That market solution establishes the foundation from which the model steps forward to the next time period. Other IAMs, such as MERGE and MESSAGE, are built on an intertemporal optimization framework. These models solve all periods simultaneously so that expectations about the future are consistent with the model's future realizations in each time period. In contrast, GCAM, and other dynamic-recursive models, do not assume such intertemporal optimization takes place. Decisions taken in one period contain only expectations about future market conditions. These expectations will not necessarily be realized in the future. In other words, the economic agents in GCAM make decisions based on a less-than-perfect foresight, and the agents' only recourse in the subsequent period is to make another set of decisions, which can also be suboptimal.

The GCAM's time step is variable, but in general is set to 5 years, which is relatively common among integrated assessment models. GCAM tracks 16 different greenhouse gases, aerosols, and short-lived species. The GCAM physical atmosphere and climate are represented by the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC) [27–29].

In the remainder of this section, we discuss in more detail two of the most important model components in GCAM: the representation of the energy system and the representation of agriculture and land use more generally.

The Energy System in GCAM

In GCAM, the energy system represents processes of energy resource extraction, transformation, and delivery, ultimately producing services demanded by end users
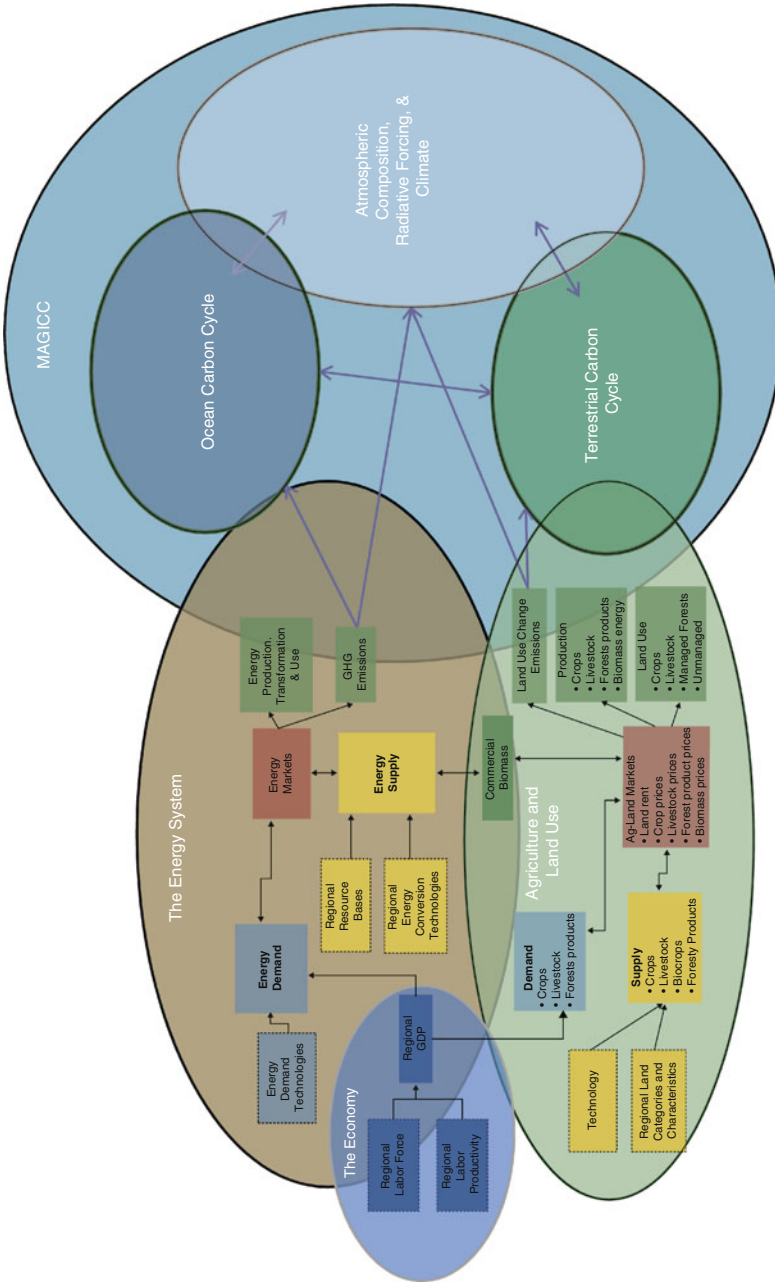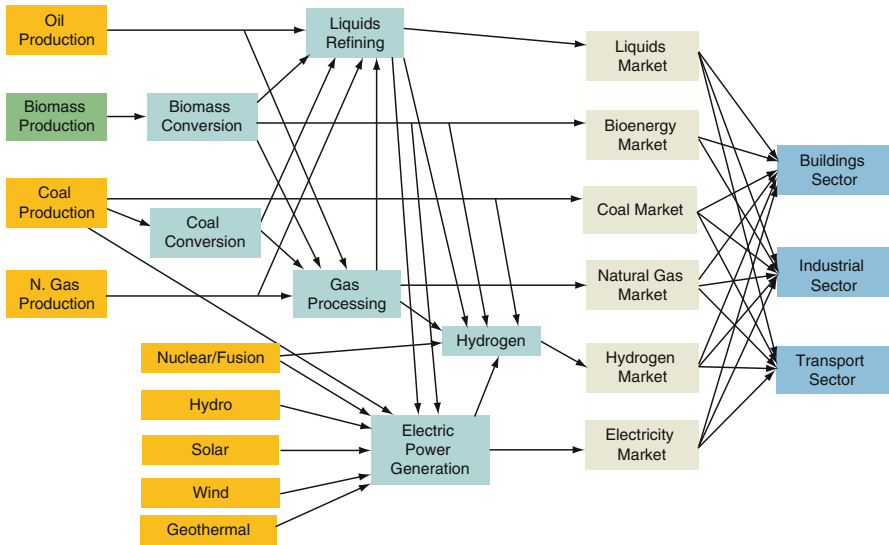
Fig. 8.2 Human and natural Earth systems of the global change assessment model

Fig. 8.3 The energy system in GCAM

(Fig. 8.3). In each time period, the market prices of all goods and services, including primary energy resources, land, agricultural goods, and other products, are determined by the market equilibrium.

Primary energy production is limited by regional resource availability. Fossil fuel and uranium resources are finite, graded, and depletable. Wind, solar, hydro, and geothermal resources are also finite and graded, but renewable. Bioenergy is also renewable, but is treated as an explicit product of the agriculture-land-use portion of the model. Extraction costs for graded resources rise as the resource consumption increases, but can fall with improvement in extraction technologies, and can rise or fall depending on other environmental costs.

Primary energy forms can be transformed into six final energy products:

- Refined liquid energy products (oil and oil substitutes)
- Processed gas products (natural gas and other artificially gasified fuels)
- Coal
- Bioenergy solids (various forms of biomass)
- Electricity
- Hydrogen

Energy transformation sectors convert resources initially into fuels, which may be consumed by either other energy transformation sectors or ultimately into goods and services consumed by end users. In each energy sector, multiple technologies compete for market share; shares are allocated among competing technologies using a logit choice formulation [30–32]. The cost of a technology in any period is determined by two key exogenous input parameters – the nonenergy cost and the efficiency of energy transformation – as well as the prices of the fuels it consumes. The nonenergy cost

Table 8.3 Residential sector efficiencies by service and technology (Source: Kyle et al. [79])

Residential				Reference		Advanced	
Service	Technology	unit	2005	2050	2095	2050	2095
	Building shell	W/m^2	0.232	0.182	0.150	0.163	0.125
Heating	Gas furnace	Out/in	0.82	0.90	0.97	Same as Ref	
	Gas heat pump	Out/in	n/a	n/a	n/a	1.75	2.45
	Electric furnace	Out/in	0.98	0.99	0.99	Same as Ref	
	Electric heat pump	Out/in	2.14	2.49	2.79	2.94	4.12
	Oil furnace	Out/in	0.82	0.86	0.93	Same as Ref	
	Wood furnace	Out/in	0.40	0.42	0.44	Same as Ref	
Cooling	Air conditioning	Out/in	2.81	3.90	4.88	4.59	7.19
Water heating	Gas water heater	Out/in	0.56	0.61	0.64	0.79	0.88
	Gas HP water heater	Out/in	0.89	1.09	1.22	1.75	2.45
	Electric water heater	Out/in	0.88	0.93	0.97	Same as Ref	
	Electric HP water heater	Out/in	n/a	2.46	2.75	2.75	3.45
	Oil water heater	Out/in	0.55	0.56	0.59	Same as Ref	
Lighting	Incandescent lighting	Lumens/W	14	15	16	Same as Ref	
	Fluorescent lighting	Lumens/W	60	75	94	Same as Ref	
	Solid-state lighting	Lumens/W	100	112	125	156	245
Appliances	Gas appliances	Indexed	1.00	1.12	1.25	Same as Ref	
	Electric appliances	Indexed	1.00	1.23	1.38	1.44	2.01
Other	Other gas	Indexed	1.00	1.12	1.25	Same as Ref	
	Other electric	Indexed	1.00	1.08	1.21	1.40	1.96
	Other oil	Indexed	1.00	1.12	1.25	Same as Ref	

represents all fixed and variable costs incurred over the lifetime of the equipment
(except for fuel costs), amortized into a unit cost of output. For example, a coal-fired
electricity plant incurs a range of costs associated with construction (a capital cost)
and annual operations and maintenance. The efficiency of a technology determines
the amount of fuel required to produce each unit of output (e.g., the fuel efficiency of
a vehicle in passenger-km per GJ, or the electricity generation efficiency of a coal-
fired power plant). The prices of different fuels are calculated endogenously in each
time period based on supplies, demands, and resource depletion.

The representation of energy technologies in GCAM is highly disaggregated.
Table 8.3 shows, for example, the set of technologies with accompanying
assumptions of technology change over time, for the detailed US representation of
residential buildings in GCAM.

Other energy sectors in GCAM have similar, high degrees of technology disag-
gregation. There are, for example, multiple technology options for generating
electric power which include a variety of technologies utilizing solar energy as
well as technology options to capture, transport, and store CO_2 in geologic
repositories (CCS). The deployment of CCS technology in conjunction with
bioenergy is of special interest in the consideration of very low long-term limits
on CO_2 concentrations in that this combination potentially allows the production of
energy with negative net CO_2 emissions. We discuss this particular technology
combination in greater detail in a subsequent section of this entry.

Agriculture and Land Use in GCAM

### Overview of the Agriculture and Land-Use Model in GCAM

Land use is one of the largest anthropogenic sources of emissions of greenhouse gases, aerosols, and short-lived species. The conversion of grasslands and forests to agricultural land results in a net emission of CO_2 to the atmosphere. In the nineteenth century, the conversion of forests to agricultural land was the largest source of anthropogenic carbon emissions. In the future, biomass energy crops could compete for agricultural land with traditional agricultural crops, providing a crucial linkage between land use and the energy system. Efforts to sequester carbon in terrestrial reservoirs, such as forests, may limit deforestation activities, and potentially lead to afforestation or reforestation activities. Interactions with crop prices may also prove important. Since land is limited, increasing the demand for land either to protect forests or to plant bioenergy crops could put upward pressure on crop prices that would not otherwise occur [33].

Many higher resolution IAMs include representations of agriculture, land use, and land cover. For some models, such as IGSM or IMAGE, a separate ecosystem model is used to represent terrestrial systems, which is then loosely coupled to the other elements of the IAM. These models represent land use, land cover, and the terrestrial carbon cycle. The IGSM model employs the Terrestrial Ecosystems Model [23], while IMAGE employs their terrestrial environment system submodel [34]. Since these models represent terrestrial processes at fine geographic scales – ½ degree by ½ degree gridded maps, for example – land use is determined by coupling an aggregated model of agriculture with a downscaling algorithm.

GCAM uses a model of land use and land cover, which allocates land area within each of its 14 global geopolitical regions among different land uses and tracks production from these uses and corresponding carbon flows into and out of terrestrial reservoirs. The GCAM agriculture, land use, land cover, terrestrial carbon cycle module determines the demands for and production of agricultural products, the prices of these products, the allocation of land to competing ends, and the carbon stocks and flows associated with land use.

Land is allocated between alternative uses based on expected profitability, which in turn depends on the productivity of the land-based product (e.g., mass of harvestable product per hectare), product price, and non-land costs of production (labor, fertilizer, etc.). The allocation of land types takes place in the model through global and regional markets for agricultural products. These markets include those for raw agricultural products as well as those for intermediate products such as poultry and beef. Demands for most agricultural products, with the exception of biomass products, are driven primarily by income and population. Land allocations evolve over time through the operation of these markets, in response to changes in income, population, technology, and prices.

The boundary between managed and unmanaged ecosystems is assumed to be elastic in GCAM. The area of land under cultivation expands and contracts as crops
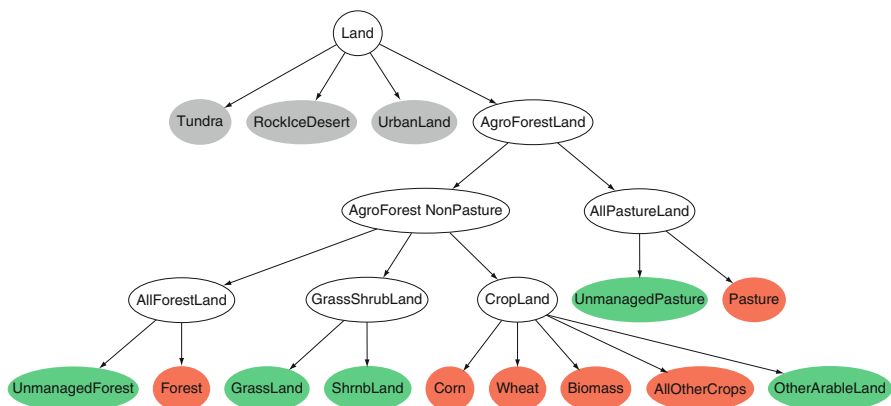
Fig. 8.4 *Competition for land in GCAM*. *Gray* exogenous in future periods, *Green* unmanaged land use, *Red* managed land use. AgLU tracks carbon content in different land uses. Changes in land use result in carbon flux to the atmosphere. Land owners compare economic returns across crops, biomass, pasture, and (future) forest, based on underlying probability distribution of yields per hectare

become more or less profitable. Thus, increased demands for land result in higher cropland profitability and expansion into unmanaged ecosystems and vice versa. Competition between alternative land uses in the GCAM is modeled using a nested logit architecture [30–32] as depicted in Fig. 8.4.

The costs of supplying agricultural products are based on regional characteristics, such as the productivity of land and the variable costs of producing the crop. The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. It has been shown that the rate of crop yield improvement is a critical determinant of land-use change emissions [33, 35–37].

Bioenergy in GCAM's Agriculture and Land-Use Model

Bioenergy supply is determined by the agriculture-land-use component (AgLU) of GCAM, while bioenergy demand is determined in the energy component of the model. For example, the larger the value of carbon, the more valuable biomass is as an energy source and hence the greater the price the energy markets will be willing to pay for biomass. Conversely, as populations grow and incomes increase, competing demands for land may drive down the amount of land that would be available for biomass production at a given price.

There are three types of bioenergy produced in GCAM: traditional bioenergy production and use, bioenergy from waste products, and purpose-grown bioenergy. Traditional bioenergy consists of straw, dung, fuel wood, and other energy forms that are utilized in an unrefined state in the traditional sector of an economy. Traditional bioenergy use, although significant in developing nations, is

a relatively small component of global energy. Traditional bioenergy is modeled as a function of regional income levels with its use diminishing as per capita incomes rise.

Other two types of bioenergy products are fuels that are consumed in the modernized sectors of the economy. Bioenergy from waste products are by-products of another activity. Examples in the model include forestry and milling by-products, crop residues in agriculture, and municipal solid waste. The availability of byproduct energy feedstocks is determined by the underlying production of primary products and the cost of collection. The total potential agricultural waste available is calculated as the total mass of the crop less the portion that is harvested for food, grains, and fibers, and the amount of bioenergy needed to prevent soil erosion and nutrient loss and sustain the land productivity. The amount of potential waste that is converted to bioenergy is based on the price of bioenergy.

The third category of bioenergy is purpose-grown energy crops. Purpose-grown bioenergy refers to crops whose primary purpose is the provision of energy. These would include, for example, switchgrass and woody poplar. The profitability of purpose-grown bioenergy depends on the expected profitability of growing and selling that crop relative to other land-use options in GCAM. This in turn depends on numerous other model factors: in the agricultural sector, bioenergy crop productivity (which in turn depends on the character of available land as well as crop type and technology) and nonenergy costs of crop production, and in the fuel processing sector, cost and efficiency of transformation of purpose-grown bioenergy crops to final energy forms (including liquids, gases, solids, electricity, and hydrogen), cost of transportation to the refinery, and the price of final energy forms. Furthermore, the price of final energy forms is determined endogenously as a consequence of competition between alternative energy resources, transformation technologies, and end-use energy service delivery technologies. In other words, prices are determined so as to simultaneously match demand and supplies in all energy markets as well as all land-use markets.

A variety of crops could potentially be grown as bioenergy feedstocks. The productivity of those crops will depend on where they are grown – which soils they are grown in, climate characteristics and their variability, whether or not they are fertilized or irrigated, the availability of nitrogen and other minerals, ambient CO_2 concentrations, and their latitude. GCAM typically include a generic bioenergy crop, with its characteristics similar to switchgrass that is assumed to be grown in all regions. Productivity is based on region-specific climate and soil characterizes and varies by a factor of three across the GCAM regions. GCAM allows for the possibility that bioenergy could be used in the production of electric power and in combination with technologies to provide CO_2 emissions captured and stored in geological reservoirs (CCS). This particular technology combination is of interest because bioenergy obtains its carbon from the atmosphere and if that carbon were to be captured and isolated permanently from the atmosphere the net effect of the two technologies would be to produce energy with negative CO_2 emissions. See, for example, [33, 38].

Pricing Carbon in Terrestrial Systems

Efficient climate policies are those that apply an identical price to greenhouse gas emissions wherever they occur. Hence, an efficient policy is one that applies identical prices to land-use change emissions and fossil and industrial emissions. This efficient approach is used as the default for emissions mitigation scenarios, though other policy options have also been modeled (A change in atmospheric CO_2 concentration has the same impact on climate change no matter what the source. Thus, to a first approximation land-use emissions have the same impact as fossil emissions. But, there are important differences. Land-use emissions do not have the same impact on atmospheric concentrations as fossil emissions because land-use emissions also imply changes in the future behavior of the carbon cycle. A tonne of carbon emitted due to deforestation, for example, is associated with a decrease in forest that would otherwise act as a carbon sink in the future. This effect, however, is not currently captured in GCAM).

Carbon in terrestrial systems can be priced using either a flow approach or a stock approach. The flow approach is analogous to the pricing generally discussed for emissions in the energy sector: landowners would receive either a tax or a subsidy based on the net flow of carbon in or out of their land. If they cut down a forest to grow bioenergy crops, then they would pay a tax on the CO_2 emissions from the deforestation. In contrast, the stock approach applies a tax or a subsidy to landowners based on the carbon content of their land. If the carbon content of the land changes, for example, by cutting forests to grow bioenergy crops, then the tax or subsidy that the landowner receives is adjusted to represent the new carbon stock in the land. The stock approach can be viewed as applying a "carbon rental rate" on the carbon in land. Both approaches have strengths and weaknesses. Real-world approaches may not be explicitly one or the other. By default, GCAM uses the stock approach.

Using Higher Resolution IAMs to Analyze the Impact of Policies to Mitigate Greenhouse Gas Emissions

A Brief Overview of IAMs in Mitigation Policy Analysis

Higher resolution IAMs have been used extensively to estimate the effects of measures to reduce greenhouse gas emissions. Until recently, the great bulk of the literature focused on the analysis of idealized policy instruments, particularly carbon taxes and cap-and-trade policies. For example, an important vein of early analysis focused on the question of emissions trading. In general, this literature showed that emissions mitigation undertaken with tradable permits resulted in lower costs to all parties without any reduction in overall emissions mitigation (see, for example, [39, 78]. The basic architecture of the Kyoto Protocol [40]

reflected this line of thought. The application of these idealized pollution pricing mechanisms was inherently straightforward in higher resolution IAMs because these IAMs' representations of the energy and terrestrial systems are all built on economic principles. Furthermore, these mechanisms were of interest because they were theoretically attractive for the efficiency with which they reduced emissions.

In all the stabilization scenarios, the carbon price rises, by design, over time until stabilization is achieved (or the end-year 2100 is reached), and the prices are higher the more stringent is the stabilization level. There are substantial differences in carbon prices between MERGE and MiniCAM stabilization scenarios, on the one hand, and the IGSM stabilization scenarios on the other. Differences between the models reflect differences in the emissions reductions necessary for stabilization and differences in the technologies that might facilitate carbon emissions reductions, particularly in the second half of the century.

Whether for CO_2 or for multiple gases, a major focus of analysis has been to compute minimum-cost emissions trajectories for meeting long-term stabilization goals. The minimum cost is generally calculated on the assumption that all regions of the world undertake emissions mitigation in a coordinated, intertemporal program that reduces emissions in an economically efficient manner. One key characteristic of this pathway is that the marginal cost of emissions mitigation is equal in all sectors and in all regions at any point in time. It also means that the price of CO_2 rises at the rate of interest plus the rate of removal of CO_2 from the atmosphere until stabilization is reached [41]. After stabilization is reached, the CO_2 price no longer rises at this roughly constant rate, but instead is determined so as to ensure that at any point in time emissions match uptake so concentrations remain constant. Examples of classic stabilization CO_2 price pathways are shown in Fig. 8.5.

While mitigation cost may be one of the core questions addressed by the higher resolution IAMs, it is not the only question. A second and complementary set of questions focuses on implications for energy and agricultural systems, the next level of detail upon which higher resolution IAMs focus. How fast must the energy system change? Which technologies need to be deployed and when (see, e.g., [42, 43])? Stabilization of the concentration of CO_2 at any level requires that net anthropogenic carbon emissions must peak and decline indefinitely toward zero [1], but an almost infinite set of combinations of technology could in principle deliver that outcome. For example, fossil fuel use could be replaced with renewable energy forms in combination with energy efficiency improvements. Alternatively, fossil fuels could continue to be deployed in the global energy system in combination with CO_2 capture and storage (CCS), nuclear power, renewable energy, and energy efficiency. The combinations that emerge from different models depend on assumptions about technology performance and availability, scale of the economic system, and climate policy. A wide range of studies has made evolution of the energy system to meet long-term goals a focus of analysis (see, e.g., Fig. 8.6 from [14]).
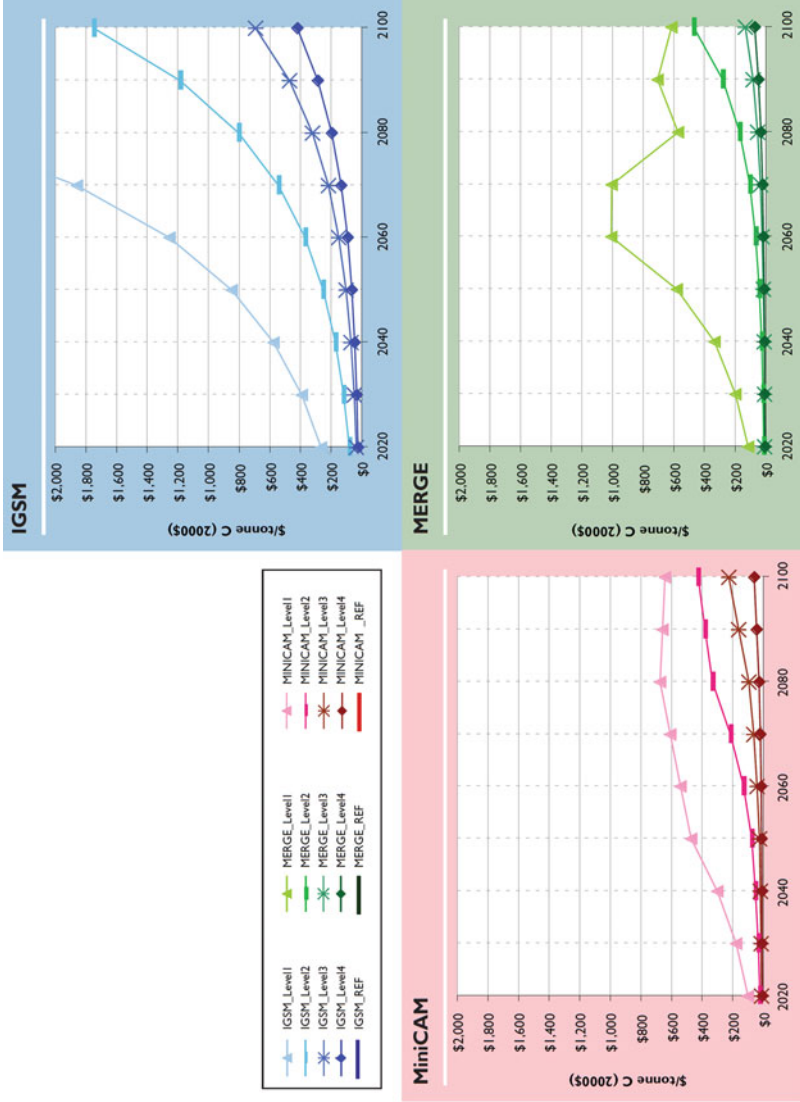
Fig. 8.5 Carbon prices across stabilization scenarios ($/ton C, 2000$) from three higher resolution IAMs leading to stabilization at approximately 750 ppmv CO_2 (Level 4), 650 ppmv CO_2 (Level 3), 550 ppmv CO_2 (Level 2), and 450 ppmv CO_2 (Level 1) (Source: Clarke et al. [14])
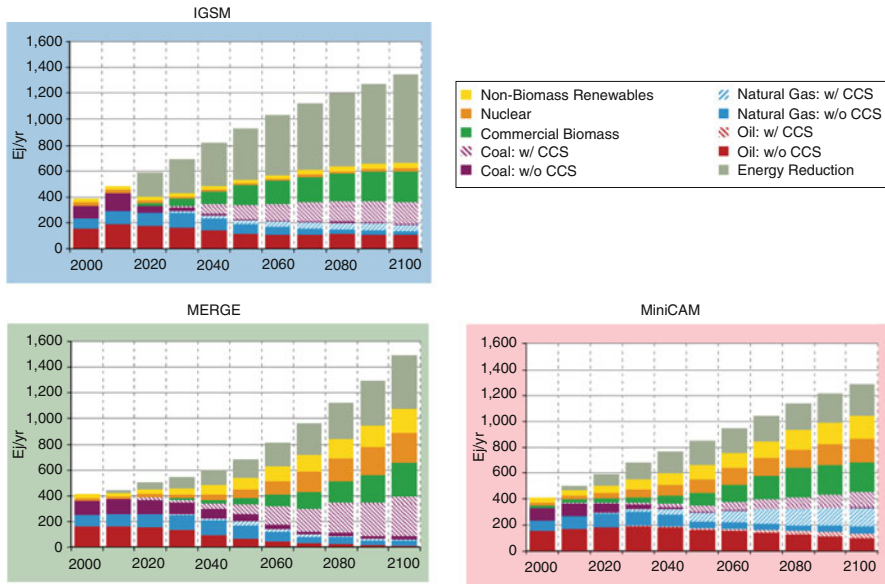
Fig. 8.6 Global primary energy production across scenarios from three higher resolution IAMs leading to approximately 450 ppmv CO_2 (Source: Clarke et al. [14])

Stabilization in IAMs with Multiple Greenhouse Gases

The United Nations Framework Convention on Climate Change (UNFCCC) has as its goal the stabilization of the concentration of greenhouse gases in the atmosphere. As discussed above, examination of the cost of stabilization of CO_2 and other gases has been the focus of a great number of papers utilizing higher resolution IAMs. Early studies focused exclusively on stabilization. However, more recent efforts have explored stabilization considering multiple greenhouse gases [14, 44].

When multiple greenhouse gases are considered simultaneously the problem emerges as to how to compare the greenhouse effects across the various constituents. In terms of climate change, the natural aggregate measure is radiative forcing (see Box 8.2). It is relatively straightforward to compute the radiative forcing for a group of gases, aerosols, and short-lived species and then to estimate what concentration of CO_2 would yield that radiative forcing level if all other species were set at their preindustrial levels. The answer to that question is the CO_2-equivalent concentration for that bundle of gases.

Two approaches have been used to determine the optimal mix of abatement across gases in stabilization. One approach is to minimize the total costs of meeting a long-term radiative forcing target, based on the combined mitigation costs for all greenhouse gases using intertemporal optimization. This is the approach employed by intertemporal optimization models such as MERGE. In this structure, all of the prices of the different greenhouse gases rise at relatively constant rates until

Box 8.2. Radiative Forcing

Most of the Sun's energy that reaches the Earth is absorbed by the oceans and land masses and radiated back into the atmosphere in the form of heat or infrared radiation. Some of this infrared energy is absorbed and reradiated back to the Earth by atmospheric gases, including water vapor, CO_2, and other substances. As concentrations of GHGs increase, there are direct and indirect effects on the Earth's energy balance. The direct effect is often referred to as a radiative forcing, a subset of a more general set of phenomena referred to as climate forcings. The National Research Council [45] offers the following set of definitions:

> Factors that affect climate change are usefully separated into forcings and feedbacks. ... A climate forcing is an energy imbalance imposed on the climate system either externally or by human activities. Examples include changes in solar energy output, volcanic emissions, deliberate land modification, or anthropogenic emissions of greenhouse gases, aerosols, and their precursors. A climate feedback is an internal climate process that amplifies or dampens the climate response to an initial forcing. An example is the increase in atmospheric water vapor that is triggered by an initial warming due to rising carbon dioxide (CO_2) concentrations, which then acts to amplify the warming through the greenhouse properties of water vapor.. ...
>
> Climate forcing: An energy imbalance imposed on the climate system either externally or by human activities.

- *Direct radiative forcing*: A climate forcing that directly affects the radiative budget of the Earth's climate system; for example, added carbon dioxide (CO_2) absorbs and emits infrared radiation. Direct radiative forcing may be due to a change in concentration of radiatively active gases, a change in solar radiation reaching the Earth, or changes in surface albedo. Radiative forcing is reported in the climate change scientific literature as a change in energy flux at the tropopause, calculated in units of watts per square meter (W/m^2); model calculations typically report values in which the stratosphere was allowed to adjust thermally to the forcing under an assumption of fixed stratospheric dynamics.
- *Indirect radiative forcing*: A climate forcing that creates a radiative imbalance by first altering climate system components (e.g., precipitation efficiency of clouds), which then almost immediately lead to changes in radiative fluxes. Examples include the effect of solar variability on stratospheric ozone and the modification of cloud properties by aerosols.
- *Nonradiative forcing*: A climate forcing that creates an energy imbalance that does not immediately involve radiation. An example is the increasing evapotranspiration flux resulting from agricultural irrigation.

Source: Clarke et al. [14], Box 1.1; NRC [45]

Table 8.4 Direct global warming potential coefficients

Industrial designation or common name (years)	Chemical formula	Lifetime (years)	Radiative efficiency ($Wm^{-2}\ ppb^{-1}$)	IPCC [48] (100^{-year})	20^{-year}	100^{-year}	500^{-year}
Carbon dioxide	CO_2	See notes[a]	[b]1.4×10^{-5}	1	1	1	1
Methane[c]	CH_4	12[c]	3.7×10^{-4}	21	72	25	7.6
Nitrous oxide	N_2O	114	3.03×10^{-3}	310	289	298	153

[a]The CO_2 response function used in this report is based on the revised version of the Bern carbon cycle model (Bern2.5CC) [49] used in IPCC [47] Chap. 10 Global Climate Projections using a background CO_2 concentration value of 378 ppm. The decay of a pulse of CO_2 with time t is given by $a_0 + \sum_{l=1}^{3} a_i \cdot e^{-t/\tau_l}$ where $a_0 = 0.217$, $a_1 = 0.259$, $a_2 = 0.338$, $a_3 = 0.186$, $\tau_1 = 172.9$ years, $\tau_2 = 18.51$ years, and $\tau_3 = 1.186$ years

[b]The radiative efficiency of CO_2 is calculated using the IPCC [50] simplified expression as revised in the TAR, with an updated background concentration value of 378 ppm and a perturbation of +1 ppm (see IPCC [47], Sect. 2.10.2)

[c]The perturbation lifetime for methane is 12 years as in the IPCC [48] (see also [47], Sect. 7.4). The GWP for methane includes indirect effects from enhancements of ozone and stratospheric water vapor (see [47], Sect. 2.10.3.1)

Source: IPCC [43], Table 2.14, pp. 212–213

stabilization is reached, consistent with the general result for minimum-cost CO_2 pathways discussed in the previous section [41], but the rates vary among gases. This leads to different timing of mitigation across gases. Indeed, one of the outcomes of this sort of approach to multi-gas stabilization is that the rate of increase in greenhouse gas prices is higher for gases with shorter lifetimes, with the implication that mitigation for these gases is delayed relative to CO_2. For example, this approach leads to scenarios in which mitigation of CH_4 is relatively modest in the early term and then increases dramatically as the total radiative forcing target gets close.

An alternative, though less rigorous methodology that is used to compare greenhouse gases in multi-gas emissions mitigation programs is the application of Global Warming Potential (GWP) coefficients. This is the approach generally used by dynamic-recursive models such as GCAM. The GWP was developed as an analogue to the Ozone Depletion Potential (ODP) coefficients employed to compare the various stratospheric ozone depleting substances [46]. GWPs are defined as the effect on radiative forcing of the release of an additional kilogram of a gas, relative to the simultaneous release of a kilogram of CO_2, integrated over one of three time horizons: 20 years, 100 years, and 500 years. Values for the GWPs calculated by IPCC Working Group I in the Fourth Assessment Report [47] are given in Table 8.4. GWPs are something of a mixture between the relative contribution of a gas to radiative forcing, which would be better calculated directly if possible, and an incomplete estimate of climate damage associated with the release of an additional kilogram of a greenhouse gas.

The primary virtue in the GWP is its application as an estimate of the relative importance of various greenhouse gases by national, local, and regional parties. Multi-gas policy instruments often employ GWPs as a means of comparing emissions of different greenhouse gases. The ratio of any pair of GWPs serves as the inverse of the relative price of any pair of greenhouse gases.

In application to stabilization studies in IAMs, GWPs yield constant estimates of the relative contributions of various greenhouse gases to climate change. In other words, since the GWPs are assumed to be constant over time, the relative prices of CO_2 and other gases are also constant over time. Hence, in studies that use GWPs to achieve multi-gas stabilization, mitigation for gases with shorter lifetimes generally takes place more quickly that would be the case in models that employ an intertemporal optimization approach. In this sense, although GWPs are a reality in policy design, they are an imperfect tool for comparing greenhouse gases over time. Manne and Richels [52] showed that if the total cost is the only criteria by which emissions pathways are judged then GWPs were not constant, but would rather change systematically with time. Peck and Wan [41] showed that if minimizing the total cost of limiting radiative forcing were the sole criterion by which greenhouse gas concentrations were controlled then the shadow price of each greenhouse gas rises at the interest rate plus the rate of removal from the atmosphere. Hence the corresponding GWP ratio of any two gases changes over time at a rate equal to the removal rate difference between the two gases. This notion is profoundly different than the concept of the GWP as a constant.

Manne and Richels [52] did show that the inclusion of secondary criteria, in addition to limiting radiative forcing, such as limiting the rate of change of radiative forcing, could produce very different GWPs and rates of change in GWPs over time. Some combinations of objective criteria could generate relatively stable GWPs.

The Economic Costs of Implementing the Framework Convention on Climate Change

As mentioned above, estimating the costs of meeting long-term targets is a primary function of IAMs. Typical estimates for global costs of limiting CO_2 equivalent concentrations to alternative levels from the IPCC [43] are shown below for two representative years, 2030 (Table 8.5) and 2050 (Table 8.6).

While the question of the measurement of the economic cost of emissions mitigation has not generated as much debate as questions about discounting, there are important differences in methodology that different modeling teams employ. Perhaps the most commonly used metric comparable across models is the price of carbon. This metric is useful for comparing across models when simple policy instruments to mitigate emissions are employed – specifically either an economy-wide carbon tax or the carbon price emerging from an economy-wide cap-and-

Table 8.5 Estimated global macroeconomic costs in 2030[a] for least-cost trajectories toward different long-term stabilization levels[b, c]

Stabilization levels (ppm CO_2-eq)	Median GDP reduction[d] (%)	Range of GDP reduction[d, e] (%)	Reduction of average annual GDP growth rates[d, f] (percentage points)
590–710	0.2	−0.6 to 1.2	<0.06
535–590	0.6	0.2 to 2.5	<0.1
445–535[g]	Not available	<3	<0.12

[a]For a given stabilization level, GDP reduction would increase over time in most models after 2030. Long-term costs also become more uncertain
[b]Results based on studies using various baselines
[c]Studies vary in terms of the point in time stabilization is achieved; generally this is in 2100 or later
[d]These are global GDP-based market exchange rates
[e]The median and the 10th and 90th percentile range of the analyzed data are given
[f]The calculation of the reduction of the annual growth rate is based on the average reduction during the period till 2030 that would result in the indicated GDP decrease in 2030
[g]The number of studies that report GDP results is relatively small and they generally use low baselines
Source: IPCC [43], SPM, p. 12

Table 8.6 Estimated global macroeconomic costs in 2050 for least-cost trajectories toward different long-term stabilization levels[a]

Stabilization levels (ppm CO_2-eq)	Median GDP reduction[b] (%)	Range of GDP reduction[b, c] (%)	Reduction of average annual GDP growth rates[b, d] (percentage points)
590–710	0.5	−1 to 2	<0.05
535–590	1.3	Slightly negative-4	<0.1
445–535[e]	Not available	<5.5	<0.12

[a]This corresponds to the full literature across all baselines and mitigation scenarios that provide GDP numbers
[b]These are global GDP-based market exchange rates
[c]The median and the 10th and 90th percentile range of the analyzed data are given
[d]The calculation of the reduction of the annual growth rate is based on the average reduction during the period until 2050 that would result in the indicated GDP decrease in 2050
[e]The number of studies is relatively small and they generally use low baselines. High emissions baselines generally lead to higher costs
Source: IPCC [43], SPM, p. 18

trade. As policy assumptions become more complex the usefulness of this metric fades. In fact, in mixed emissions mitigation systems, where only part of the economy is controlled by a tax or cap-and-trade program, the carbon price and real economic cost can move in opposite directions. That is, as more of the high-cost sectors of the economy are controlled with less-efficient nonmarket-based policies, the price of carbon may fall while the total economic cost rises.

A variety of approaches have been applied to obtain the total economic cost. These include integration under the marginal abatement cost schedule, measurement of foregone consumption, and compensated/equivalent variation. Each of these approaches traces its method back to welfare economics. While measures that directly link to welfare functions are in principle best, welfare cannot be

directly observed and unless highly unlikely circumstances prevail, Arrow [53] has shown that a welfare function with the properties needed to get a measure on real economic cost cannot exist – a distinct disadvantage for numerical simulations.

While the choice of methodological approach to measuring real economic cost will doubtless affect valuation, two larger sources of variation in cost estimates are the policy instruments applied and the assumed rate of technological improvement. It is well known that different policy instruments can attain the same mitigation level with different costs [54]. Differences in technology assumptions can also produce substantial differences in cost (see, e.g., [42, 55]). Exploring the implication of different policy instruments and technology availability are two important directions of future work by the higher resolution IAM research community.

The principal research question which the higher resolution IAMs addressed has been different from that of the highly aggregated IAMs. Whereas the highly aggregated IAMs focused on the problem of determining the optimal balance between emissions mitigation and adaptation to climate change, the higher resolution IAMs focused more on the cost of implementing a policy to limit emissions, concentrations, or combined radiative forcing of greenhouse gases. The higher resolution IAM community has generally taken an agnostic position on the question of whether the policy instrument or the policy goal in question was desirable or not and simply went about the task of calculating the cost of achieving the given goal of implementing the prescribed policy.

As time has passed, the political conversation has moved away from the question of the use of cap-and-trade to control emissions to consider hybrid policy architectures in which emissions mitigation is pursued through a combination of policy measures some of which differ substantially from the conventional market mechanisms, such as carbon taxes or cap-and-trade. For example, many current emissions mitigation proposals contain renewable portfolio standards (RPS). These policy instruments require a minimum fraction of total power generation to be provided by renewable energy forms such as wind and solar.

There are many reasons for the shift. The prospects for a comprehensive international agreement based on the principles of cap-and-trade have diminished. Many parties in the international negotiations were less concerned with economic efficiency and cost-minimization than they were with a sense of moral obligation to achieve domestic emissions mitigation targets without resorting to emission trading. Within the United States similar forces are at work. Efforts to develop a comprehensive countrywide emissions cap-and-trade system show little prospect for entering into effect. Also, the European Union and Japan have either chosen alternatives to cap-and-trade or employ cap-and-trade within limited sectors of the economy. Such policies have pushed IAMs to develop more sophisticated representations of policies in order to estimate the policy effects [56]. In the same context, the IAMs have begun to explore the implications of international regimes in which nations begin emissions mitigation at different times [57, 58].

Future Directions: Integrating Human Earth Systems with Natural Earth Systems

Integrated Assessment modeling research is a continuously evolving field. As the models have matured and diversified, researchers have pushed the development frontiers in multiple directions simultaneously in order to answer a wide range of research questions. For example, researchers have broadened the scope of the models to include more sectors of the human Earth system such as land use and agriculture. They have expanded coverage of various types of the greenhouse gases by including an increasingly diverse set of their sources and activities. They have also lengthened the time horizon of analysis, pressing past the year 2100 and multiple centuries beyond. At the same time, the researchers have elaborated the key model components by slicing each of them in smaller pieces, for example, by adding finer spatial and temporal resolution and disaggregated representation of technologies.

An increasingly prominent research frontier has been the formal integration with other fields of climate change research, namely climate modeling (CM) and impacts, adaptation, and vulnerability (IAV) research. Although many research questions do not require the use of IPCC-class models of human and natural Earth systems, others cannot be addressed adequately without the development of integrated Earth systems models. The development of integrated Earth systems models opens the door to formally modeling the simultaneous interactions between human activities, climate change, and climate change impacts on human systems.

The Representative Concentration Pathways: An Example of Interactions with Climate Models

The assessment of climate change has traditionally been a linear research process. IA researchers produce emissions scenarios which in turn are transferred to the climate modeling community for use as inputs. The climate modeling community employs these scenarios to force future climate calculations. These climate calculations are then used by IAV researchers to produce estimates of the consequences of climate change. In the past, there has been little communication or feedback between research communities. Each community conducted its research independently and left it for others to figure out how or whether to use it. Beginning in 1990, the integrated assessment modeling community began to interact with the climate modeling community, though interactions with the carbon cycle and other natural Earth system researchers go back even further (see, e.g., [59], and more generally, [60]). Moss et al. [61] provide a succinct history of scenario development, which is summarized in Fig. 8.7.
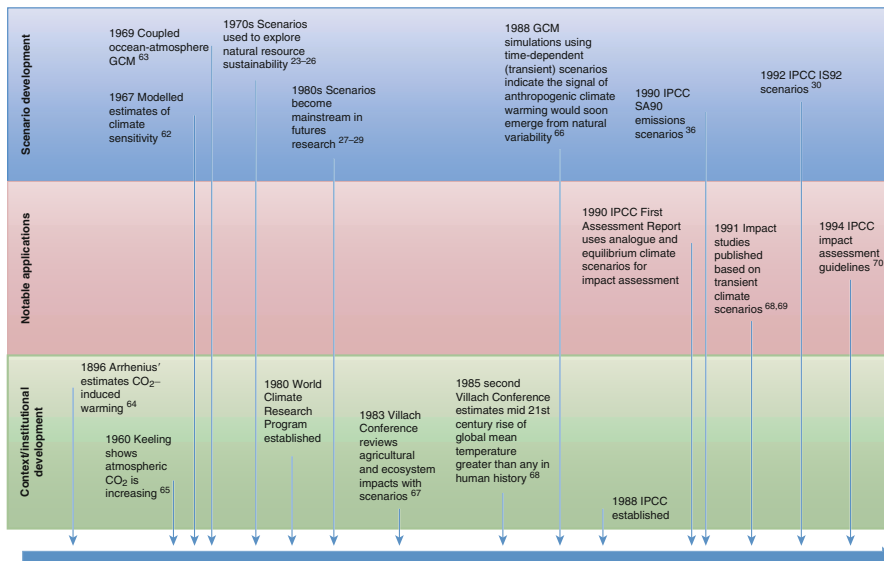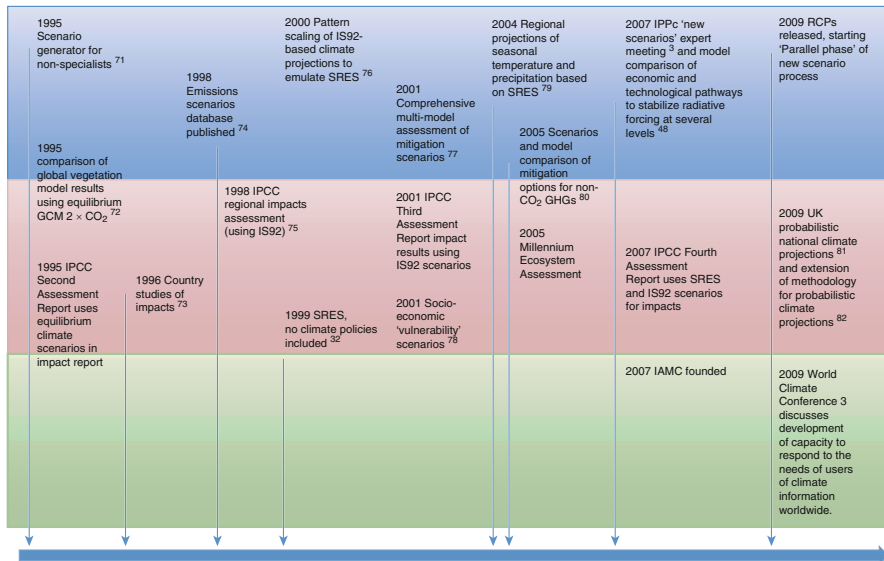
Scenario development

1969 Coupled ocean-atmosphere GCM [63]

1967 Modelled estimates of climate sensitivity [62]

1970s Scenarios used to explore natural resource sustainability [23–26]

1980s Scenarios become mainstream in futures research [27–29]

1988 GCM simulations using time-dependent (transient) scenarios indicate the signal of anthropogenic climate warming would soon emerge from natural variability [66]

1990 IPCC SA90 emissions scenarios [36]

1992 IPCC IS92 scenarios [30]

Notable applications

1990 IPCC First Assessment Report uses analogue and equilibrium climate scenarios for impact assessment

1991 Impact studies published based on transient climate scenarios [68,69]

1994 IPCC impact assessment guidelines [70]

Context/institutional development

1896 Arrhenius' estimates CO_2–induced warming [64]

1960 Keeling shows atmospheric CO_2 is increasing [65]

1980 World Climate Research Program established

1983 Villach Conference reviews agricultural and ecosystem impacts with scenarios [67]

1985 second Villach Conference estimates mid 21st century rise of global mean temperature greater than any in human history [68]

1988 IPCC established

Figure 1 | Timeline highlighting some notable developments in the creation and use of emissions and climate scenarios. The entries are illustrative of the Overall course of model-based scenario development (blue) and application (beige) described in this Perspective, and also give some context (green); they do

1995 Scenario generator for non-specialists [71]

1998 Emissions scenarios database published [74]

2000 Pattern scaling of IS92-based climate projections to emulate SRES [76]

2001 Comprehensive multi-model assessment of mitigation scenarios [77]

2004 Regional projections of seasonal temperature and precipitation based on SRES [79]

2007 IPPc 'new scenarios' expert meeting [3] and model comparison of economic and technological pathways to stabilize radiative forcing at several levels [48]

2009 RCPs released, starting 'Parallel phase' of new scenario process

1995 comparison of global vegetation model results using equilibrium GCM 2 × CO_2 [72]

1995 IPCC Second Assessment Report uses equilibrium climate scenarios in impact report

1996 Country studies of impacts [73]

1998 IPCC regional impacts assessment (using IS92) [75]

1999 SRES, no climate policies included [32]

2001 IPCC Third Assessment Report impact results using IS92 scenarios

2001 Socio-economic 'vulnerability' scenarios [78]

2005 Scenarios and model comparison of mitigation options for non-CO_2 GHGs [80]

2005 Millennium Ecosystem Assessment

2007 IPCC Fourth Assessment Report uses SRES and IS92 scenarios for impacts

2009 UK probabilistic national climate projections [81] and extension of methodology for probabilistic climate projections [82]

2007 IAMC founded

2009 World Climate Conference 3 discusses development of capacity to respond to the needs of users of climate information worldwide.

not provide a comprehensive account of all major scenarios and significant studies or assessments that have used them. See Supplementary Information for details. GCM, general circulation model; GHG, greenhouse gas; IAMC, Integrated Assessment Modelling Consortium.

Fig. 8.7 Timeline highlighting some notable developments in the creation and use of emissions and climate scenarios (Source: Moss et al. [61], pp 748–749)

There have been numerous long-term scenarios of global greenhouse gas emissions. Three important benchmarks were the publication of scenarios referred to as SA90 [51], IS92 [62], and SRES [63]. These scenarios are notable in that the climate modeling community used them to simulate potential effect of future emissions paths on the climate system. The earliest scenarios considered only fossil fuel CO_2 emissions. Over time scenarios became richer, including land-use change emissions, non-CO_2 greenhouse gases, and short-lived species. While these scenarios span a wide range of potential future emissions, none considered limitations on emissions, that is, until Moss et al. [61] and the publication of the Representative Concentration Pathways (RCPs).

The RCPs are the most recent set of scenarios developed for use in the climate models. They were chosen to initiate an assessment cycle by providing the climate modeling community with a set of scenarios that were sufficiently differentiated by the end of the century to be scientifically relevant and to provide detailed information on the sources of emissions of greenhouse gases and short-lived species from all anthropogenic sources. RCPs differ from earlier scenario development activities in that they were selected from existing scenarios that were available in the peer-reviewed literature rather than being developed de novo. Selected scenarios from the open literature were named corresponding to their century's end radiative forcing levels: 8.5, 6.0, 4.5, and 2. 6 Wm^{-2} (see Table 8.7).

Subsequent to selection, the four scenarios were updated and harmonized to include the most recent observational data and downscaled to produce harmonized gridded outputs for emissions, land use, and land cover. The resulting time-paths for radiative forcing are given in Fig. 8.8 (The detailed scenario data are available at www.iiasa.ac.at/web-apps/tnt/RcpDb/).

The RCPs differ from previous scenarios employed by the climate modeling community in that they

1. Include scenarios with explicit emissions mitigation
2. Provide geospatially resolved emissions at ½ degree by ½ degree
3. Provide geospatially resolved land use and land cover at ½ degree by ½ degree

The most recent set of scenarios, while highly useful to the climate modeling community, are less useful from the perspective of the impacts, adaptation, and vulnerability community. While the scenarios contain detailed information that would be of interest to climate modelers, they do not carry associated socioeconomic information, or energy or commodity prices.

Furthermore, even if the socioeconomic data were included for these scenarios, each of the scenarios was crafted by a different modeling team, using different assumptions about key socioeconomic and other variables. For instance, it would be difficult, if not impossible to determine if the difference in estimated impacts of climate change associated with RCP4.5 and RCP2.6 was the result of differences in the magnitude of climate change or that of differences in the underlying human Earth systems that characterize the GCAM and IMAGE scenarios, respectively.

In order to establish a framework, in which the human system impact of climate change could be coupled with emissions scenario and climate model, a new

Table 8.7 The four representative concentration pathways

Name	Radiative forcing	Concentration	Pathway	Model providing RCP	References
RCP8.5	>8.5 W/m^2 in 2100	>1,370 CO$_2$-eq in 2100	Rising	MESSAGE	Riahi et al. [64]
RCP6.0	~6 W/m^2 at stabilization after 2100	~850 CO$_2$-eq (at stabilization after 2100)	Stabilization without overshoot	AIM	Fujino et al. [65], Hijioka et al. [66]
RCP4.5	~4.5 W/m^2 at stabilization after 2100	~650 CO$_2$-eq (at stabilization after 2100)	Stabilization without overshoot	MiniCAM (GCAM)	Clarke et al. [14], Smith and Wigley [67]
RCP2.6	Peak at ~3 W/m^2 before 2100 and then decline	Peak at ~490 CO$_2$-eq before 2100 and then decline	Peak and decline	IMAGE	Van Vuuren et al. [68, 69]

Source: Moss et al. [61], p. 753

Fig. 8.8 The radiative forcing trajectories of the four RCP scenarios (Source: Moss et al. [61], P. 748–749)
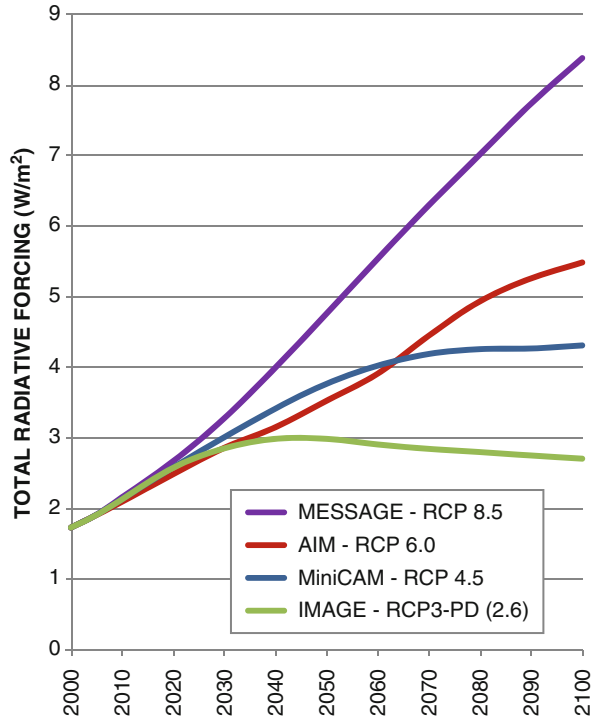
scenario matrix architecture is under development. This architecture would create a suite of scenarios that are defined in terms of two bundles of descriptors: shared socio-ecosystem pathways (SSPs) and shared climate policy assumptions (SPAs).

SSPs have three components: a set of quantitative assumptions that are used by IAMs, such as population and economic growth; a set of quantified assumptions about variables that are not part of IAMs, for example, governance index; and a narrative which describes the general state of the world and its evolution over the course of the twenty-first century.

SPAs define the state of climate policy and its evolution around the world. They are defined with quantitative descriptors, where appropriate, and a qualitative narrative. The quantitative descriptors could be, for example, a limit on radiative forcing, such as was used to define the RCPs. In addition, information regarding the nature of policies that are to be employed to affect the prescribed outcome could be included.

The virtue of harmonizing SPAs with RCPs is that the new scenarios could be coupled smoothly with climate model output from ensemble calculations. This in turn would facilitate analysis that could potentially be fully integrated across three broad research communities: climate modeling, integrated assessment modeling and impacts, and adaptation and vulnerability. Two examples of such scenario matrix architectures can be found in [70, 71].

Climate Impacts in Higher Resolution IAMs

Higher resolution IAMs are increasingly focusing on explicitly modeling the physical impacts of climate change [72]. This work builds on a long tradition of modeling climate impacts in the higher resolution IAM community (see, e.g., [26, 73–75]). However, to date higher resolution IAMs have examined climate impacts using a sequential methodology, that is, they start with emissions, which are assumed to be given by climate models, and then analyzed the consequences of the ensuing climate change.

New model development is increasingly focused on methods and tools that will allow higher resolution IAMs to examine impacts simultaneously with mitigation and therefore to allow the two to interact. For example, there are on-going research efforts that utilize the higher resolution IAMs to study scenarios in which interactions between policies to mitigate emissions through changes in land-use and land cover – e.g., afforestation policies – and adaptive responses to climate change in agricultural sectors are simultaneously examined. Two complementary model development directions are also worthy of note. First, the higher resolution models are beginning to couple with state-of-the-art natural Earth system models (discussed later in this section) and second, they are beginning to move to finer spatial and temporal resolutions.

The increasing attention to climate impacts implies that the higher resolution IAMs will produce new results that will also contribute to the impacts, adaptation, and vulnerability (IAV) research. For nonmarket impacts of climate change, higher resolution IAMs will compute physical consequences, but not necessarily economic damage estimates, as it has generally been the case with climate impacts that the higher resolution IAMs have examined to date. For climate impacts associated with marketable goods and services, economic costs can also be estimated. But, the nonlinear nature of the human and natural Earth system means that separating out the impact of emissions mitigation from the impact of climate change will be nontrivial.

A good example of new work on the interactions between mitigation and impacts within higher resolution IAMs is land use and land cover. Land use will be affected both by a changing climate and by emissions mitigation effort. Mitigation effects will take the form of forest expansion to reduce land-use change emissions along with the use of bioenergy crops for energy production. A changing climate will bring about many changes in the nature of terrestrial systems, including changes in crop yields. All of these dynamics will interact.

To illustrate these interactions, the effects of climate change on crops were modeled as a response function derived from data reported in IPCC [76]. Figure 8.9 shows the distribution of estimates of crop yields for maize and wheat for low and other latitudes.

Both a reference scenario and a policy scenario in which CO_2 concentrations were limited to stay below 500 ppm were presented. Land-use change emissions of CO_2 were recorded for the two scenarios, with and without consideration of climate feedbacks through agricultural crops. These results are displayed in Fig. 8.10.
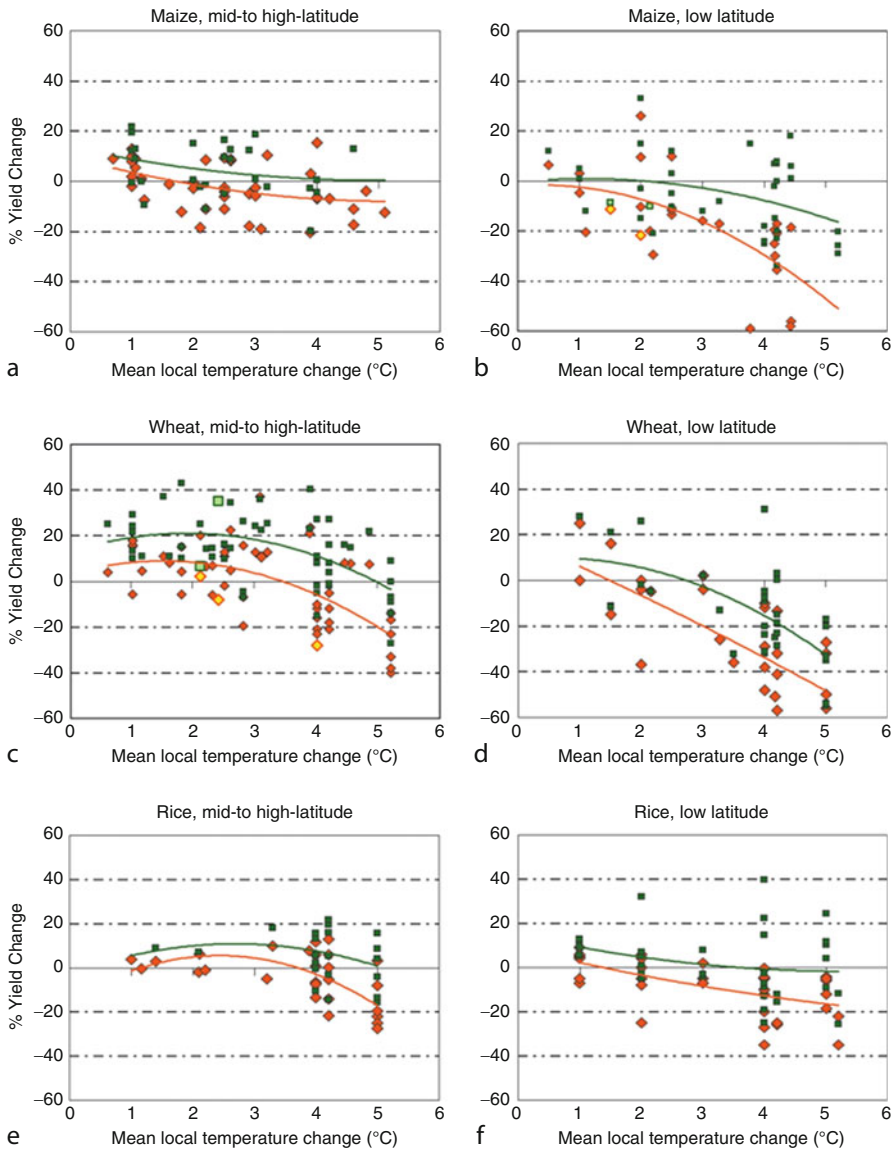
Fig. 8.9 The modeled effects of climate change on crops. Sensitivity of cereal yield to climate change for maize, wheat and rice, as derived from the results of 69 published studies at multiple simulation sites, against mean local temperature change used as a proxy to indicate magnitude of climate change in each study. Responses include cases without adaptation (red dots) and with adaptation (dark green dots). Adaptations represented in these studies include changes in planting, changes in cultivar, and shifts from rain-fed to irrigated conditions. Lines are best-fit polynomials and are used here as a way to summarise results across studies rather than as a predictive tool. The studies span a range of precipitation changes and CO_2 concentrations, and vary in how they represent future changes in climate variability. For instance, lighter-coloured dots in (**b**) and (**c**) represent responses of rain-fed crops under climate scenarios with decreased precipitation. (Source: Parry et al. [76], P. 286)
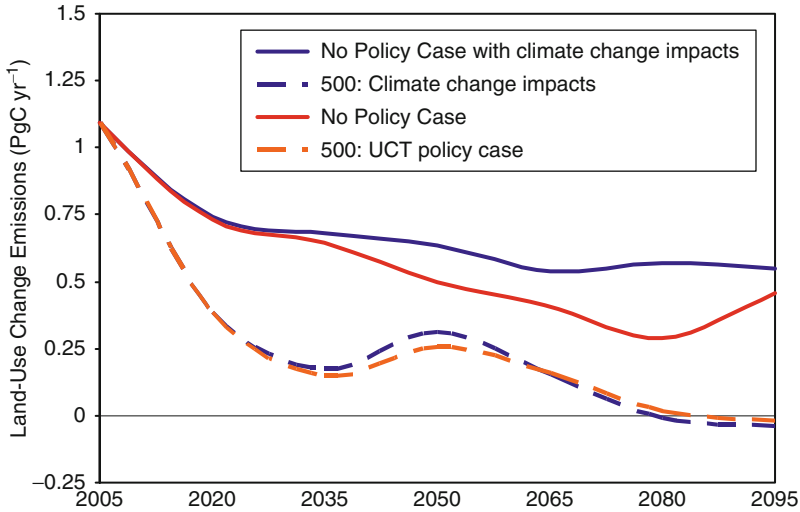
Fig. 8.10 Land-use change emissions of CO_2 under the scenarios with and without consideration of climate feedbacks through agricultural crops

Note that cumulative land-use change emissions vary significantly when climate change effects are considered in the reference scenario, with land-use change emissions significantly higher as a consequence of crop yield reductions in the face of climate change.

Results for the scenario in which CO_2 concentrations were not allowed to exceed 500 ppm exhibit lower emissions than either of the reference scenarios. This is because the mitigation scenario valued terrestrial carbon emissions equally with fossil fuel emissions (results would have been very different had terrestrial carbon not been valued; see also [33, 77]). Equally as interesting, land-use change emissions with and without consideration of climate change effects on crop yields are not significantly different between the two scenarios. This result follows directly from the fact that limiting CO_2 concentrations to 500 ppm would also limit the magnitude of climate change, which in turn moderates the effects on crop yields. The purpose of this example is not so much to showcase results, but rather to motivate the joint consideration of impacts, adaptation, and vulnerability with integrated assessment of emissions mitigation.

Linking Higher Resolution IAMs into integrated Earth System Models (iESMs)

Several research teams have undertaken joint work with the climate modeling community. The IGSM team has developed a relationship with climate researchers

at the US National Center for Atmospheric Research (NCAR). The IMAGE team has developed several collaborative relationships including those with the Oak Ridge National Laboratory (ORNL), the Centre National de Recherches Météorologiques Coupled global climate Model (CNRM-CM3) team of France, and other European climate modeling teams to develop coupled scenarios. The MESSAGE integrated assessment modeling team has developed a collaboration with the NASA Goddard Institute for Space Studies climate modeling team. The GCAM team has developed a collaboration with ORNL and the Lawrence Berkeley National Laboratory (LBNL) in the development of a modeling system that joins the Community Earth System Model (CESM) representation of natural Earth systems with the GCAM representation of human Earth systems. To date, the collaborations have produced one-way coupling models, where emission scenarios from IAMs affect the climate, while the resulting climate change does not feedback to emissions. However, current effort is focused around developing a two-way coupled system.

The goal of the joint collaborations is to create a first-generation integrated Earth System Model (iESM) by fully integrating the human dimension from an IAM and a natural dimension from a climate model, that is, to create the capability of simultaneously estimating human system impacts on climate change and climate change impacts on human systems. After creating the capacity to examine the coupled natural and human Earth systems, the project could apply the model to the examination of feedbacks between human systems, the climate systems, and land-use systems. For instance, the policy response of land-use change presented in [33] could be revisited to estimate the magnitude of feedbacks in the system.

Significant effort is required before such research becomes routine. Nonetheless, as the research potential this collaboration opens up is virtually limitless, the importance of integrating human Earth systems with natural Earth systems is sufficiently compelling to drive future collaborations between ESMs and IAMs.

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