Chapter

1

Earth system science and society: a focus on the anthropospheme

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In this chapter, we explore the challenges that Earth system researchers face in addressing human-induced global environmental changes and the societal consequences of global change within their research toolkit. We focus on areas of research that have particular resonance with today's social and political demands.

1.1 The Earth system and the 'problematic human'[1]

1.1.1 The state of play and our position

The great scientific challenge faced by today's global change scientists is to understand the Earth system. Part of this is knowing that we ourselves, as human beings, are an influential component of that system and that the understanding we develop shapes our responses to the environmental changes we see around us. In scientific terms, most of the fundamental workings of our planet, including the processes that change climate and landscapes on short and long timescales, were already well understood by the end of the twentieth century. Earth system science is the field of study that has brought these areas of knowledge together. It has not just provided insight into the phenomena of global environmental change, but also explained the 'hows' and 'whys' behind them, bringing insights into the future prospects for our planet. The enormity of the challenge lies in the realization that we are seeking to understand and predict the properties of a complex adaptive system of which we are a part, recognizing that our choices and our agency as human beings are important controls on its workings. More than that, our ability to deploy our knowledge and make choices about our actions is an important facet, perhaps even a characterizing trait, of our existence.

For scientists in all the contributing fields of inquiry, this development marks a shift from the pursuit of knowledge largely for its own sake to robust predictive knowledge that is required – urgently, many argue – for application in the real world. The prediction of any system where humans play a part has long challenged both scientists and philosophers. Without venturing into those debates here, the prediction of socio-environmental systems nevertheless presents us with a very practical conundrum: our current understanding, even the knowledge codified in the most sophisticated models, is a partial and simplified picture of reality. Our predictions based on this understanding may be wrong and the unintended consequences of action based on those predictions may be severe. However, not to use the available understanding would be to take a perverse and unhelpful position.

In this chapter, we often take the historic view, looking at past scientific efforts in global change research, particularly those efforts framed in terms of global systems. Quantitative models of human dynamics, such as Thomas Malthus' eighteenth-century calculations of Earth's carrying capacity for human population, and the Club of Rome's efforts in the 1970s to measure the limits to socio-economic growth, have generally done a poor job. Nevertheless, it is important to learn from these efforts. One reason they failed is that they did not

[1] With thanks to Lesley Head, University of Wollongong, for this expression. See Head, L. (2007) Cultural ecology: the problematic human and the terms of engagement, *Progress in Human Geography*, **31**, 837.

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adequately take into account human agency. In short, we have continually underestimated the role of the social and economic context when we have tried to model the impact of global change. Even where features of socio-economic change evident at the global level allow for a measure of scientific generalization to be made, they are often not included nor examined in models. For example, below we mention the widely observed demographic transition in human population growth: this is just as good and precise a 'law of nature' as most in biology. At the opposite end of the spectrum, there are models of the Earth system that omit human activity altogether. Contemporary physical climate models work as effectively (which is to say, very effectively indeed in describing climate dynamics) for all planets with an atmosphere, ocean and land surface. They reach the limits of their predictive power when they need to bring people into the equation. One challenge we face is that the climate modelling enterprise has defined contemporary climate change in strictly physical terms, i.e. as a physical change driven by increasing amounts of greenhouse gases in the atmosphere. However, from a socio-environmental perspective, there are many ways of looking at and defining climate change. There is a risk that using one dominant way of looking at the problem can drive the policy agenda to the exclusion of other important approaches for finding practically useful solutions. Predictive power alone is not synonymous with usefulness.

What do we require from Earth system science, defined broadly as the science of both the climate system and the human dimension (or the 'anthroposphere')? Ideally, we would like to develop a science that addresses both the human and the natural-environmental components of the system, and that can tell us something about how this complex, coupled socio-ecological system works (Young *et al.*, 2006). Modelling is an essential part of this process. uch of the remainder of this book tries to describe the present state of the models (conceptual and numerical) that underpin both the science and the political decision-making process relating to global environmental change. Earth system science should also be informed by an effective understanding of how society steers itself, so that the scientific process can be both more transparent and more responsive to the needs of society. In the context of the unprecedented magnitude and rate of global environmental changes, many people consider that major social changes are needed to cope with, manage or avert the worst impacts. These changes should involve new structures and dialogues between scientists and other members of society, for participation in collective decision-making about the future.

1.1.2 The human dimensions of global environmental change: controls, consequences and context

The rapidly expanding science of Earth's climate, biogeochemical processes, and their interconnections is complex, yet it needs to be understood much more widely if society is to respond to current environmental pressures and projected future changes in an informed way. Although our main focus in this book is on summarizing and explaining the biophysical science of global change, a deep understanding of the Earth system will also include insights from the study of human behaviour.

First of all, human activities, more than ever before, are important ***controls*** on Earth's biophysical processes.

The trajectory of human population, especially since the Industrial Revolution, has been one of steady and rapid growth. In the early nineteenth century, the political economist Thomas Malthus famously argued that unconstrained population growth would naturally follow a 'geometric ratio', or exponential growth, while the supply of life-sustaining resources would not. The result would be an overshoot of the human population and a catastrophic check (famine, disease, conflict) on human numbers. Although Malthus was plausibly describing the trends he observed, by simply extending them into the future, his predictions were very wrong. Earth's population has shown some periods of exponential growth – for instance, doubling from 1.5 billion to 3 billion inhabitants between about 1880 and 1960 (80 years), and then again to 6 billion between 1960 and 2000 (40 years). But it is unlikely that the Earth's human population will double again, so both the unfolding of history and a more sophisticated understanding of the dynamics of population have now removed the spectre of catastrophic overpopulation (Cohen 1998). In 2011, world population reached 7 billion inhabitants (United Nations, 2011), and current estimates suggest that our numbers will peak at approximately 9 billion sometime over the next century (Lutz *et al.*, 2008; United Nations, 2011). Malthus was wrong because he failed to predict the 'demographic transition', a widely observed phenomenon where birth *and* death rates both fall as economic development progresses (e.g. Chesnais, 1992), halting the exponential pattern of growth. Rates of growth of global population have declined in the last two or three decades (US Census Bureau, 2011). Malthus also failed to predict the Haber–Bosch process for nitrogenous fertilizer production and the hybridization of seeds (along with other technological innovations and transformations in agricultural systems), which have made it possible for the world to produce enough food for today's population. Today, the problem of hunger is primarily one of economics and politics affecting food supplies, not one of Earth's capacity for food production. So, while some argue that the world will need to produce considerably more food by mid-century (Bruinsma, 2009), others point out that using the food we currently have more efficiently should be enough to continue feeding the world (Smil, 2001).

Steffen *et al.* (2004) reviewed the impacts on Earth of this rapid population growth, finding similar rapid rises in natural resource use (Figure 1.1), bringing unintended consequences for ecosystems such as rising levels of air and water pollution and environmental degradation. However, the impact of human activity on the natural environment is far from being a simple linear function of population. The widely quoted 'IPAT equation' (Ehrlich and Holdren, 1971; Commoner, 1972; Box 1) frames the environmental impact of human activities as a function of technological change and economic growth as well as population: impact = *f*(population × affluence × technology). It highlights the fact that society's increasing technological capability (the *T* in the equation) means people can access more of Earth's natural resources and transform them for their use more effectively, and also that increased affluence (*A*) enables individuals in the population to use and consume more resources. The analysis conducted by Steffen *et al.* (2004) shows how affluence and technology are often much more influential on impact than population numbers.

Box 1.1 The IPAT equation

A simple formulation that has widely been used in Earth system science describes the *impact* of human activity on the natural environment as a function of *population*, *affluence* and *technology*. The interactions of these three terms have been explored empirically in a range of socio-environmental contexts, including resource consumption, food security and energy-systems analysis.

$$I\text{mpact} = f(\text{Population, Affluence, Technology})$$

The relationship between impact and the PAT terms is not simple (Chertow 2001). The original equation was simply multiplicative ($I = P \times A \times T$). This is a useful heuristic for linking impact and socio-economic development, and many nations in the world have shown increasing impacts as they developed in the past, but it is not a predictive law. Empirical studies show strongly non-linear relationships between the terms (Dietz and Rosa, 1997, Dietz *et al.*, 2007). Recent studies (e.g. Pitcher 2009, Davis and Caldeira 2010) highlight the fact that consumption levels (the *A* and *T* dimensions) are the 'thermostats' on impact, not population itself, warning against the errors of simple Malthusianism and using the formulation in 'green-revolution' arguments for technological innovation to reduce impact.

A close relative of the IPAT equation, the Kaya Identity (Kaya and Yokobori, 1993) has been developed in the context of energy and greenhouse-gas emissions. It has been applied in IPCC emission studies and scenario development (IPCC, 2001).

$$CO_2 \text{ emissions} = \text{Population} \times \underset{\text{(goods consumed per capita)}}{\text{Consumption intensity}} \times \underset{\text{(energy input per unit goods)}}{\text{Energy intensity}} \times \underset{(CO_2 \text{ output per unit energy})}{\text{Carbon intensity}}$$

These formulations show that multi-pronged responses to environmental impact can – and should – be explored. Thus, for climate change, responses could include societal learning and change, economic incentives and instruments, improved efficiency, energy substitution, CO_2 sequestration.

The impact of the human endeavour is now manifest at the global scale (Figure 1.2). Only the most hostile environments – deserts, ice-covered lands and seas, and some of the densest areas of forest remote from population centres – can still be regarded as near-pristine. The rates of human-induced changes to land, marine and atmospheric environments and the fact that they have become discernible at the global scale, have prompted a proposal for the adoption of the term 'Anthropocene' as a geological period. This is not merely a light-hearted neologism to describe contemporary environmental change: stratigraphers are engaging in international discussions about the merit and feasibility of defining a period of human perturbation of the global environment, and designating the Anthropocene as a formal unit of geological time (Zalasiewicz *et al.* 2010).

The second important reason that Earth system science needs to give attention to knowledge from

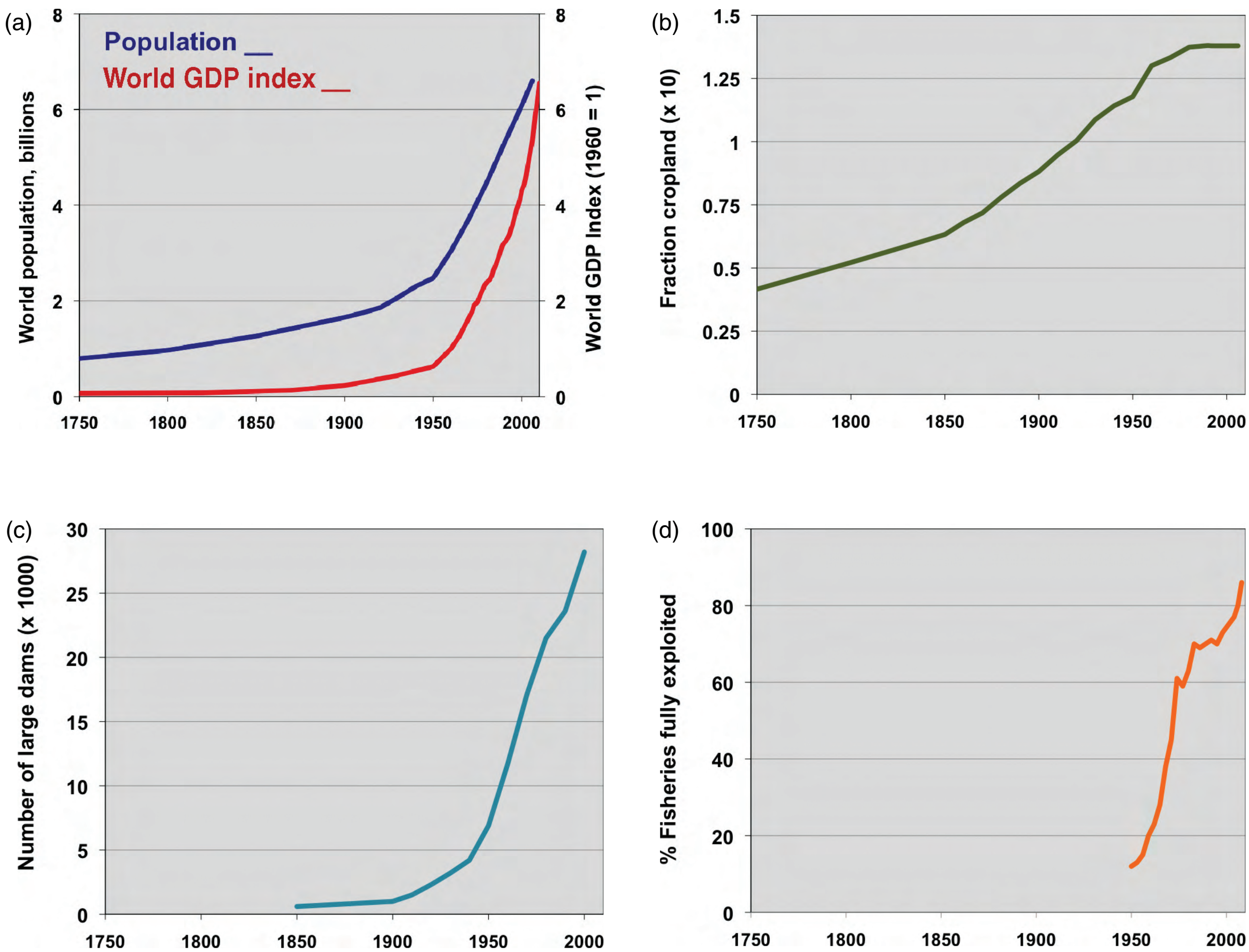

Figure 1.1 Some global socio-environmental trends since industrialization.

(a) World human population (US Bureau of the Census International Database, www.census.gov/ipc/www/worldpop.html; solid line) and the aggregate world gross domestic product indexed against 1960 world GDP (dashed line; data up to 2005 from the Earth Policy Institute, www.earth-policy.org/indicators/C53; updated to 2010 with data from the International Monetary Fund World Economic Outlook, www.imf.org/external/pubs/ft/weo).
(b) Global land use as cropland (Ramankutty and Foley, 1999; fraction of total land area multiplied by 10 for convenient scaling).
(c) Number of dams larger than 15 m on the world's rivers (data from World Commission on Dams (2000), including estimates for 2000 shown in the annex of that report).
(d) Percentage of global fisheries that are fully exploited, overfished or depleted (data from 1974 to present from FAO (2010); earlier data from FAOSTAT (2002) statistical databases, cited in Steffen *et al.*, 2004).

the social sciences is that humans experience the ***consequences*** of global environmental change.

The fact that the natural environment presents hazards to people is nothing new Newspapers are full of reports of humanitarian disasters caused by droughts, floods, storms and other geological and climatic events. Similarly, it is widely recognized that human society has the capability to create serious environmental risks for itself. Communities, societies and, arguably, entire empires, have done so in the past with catastrophic consequences (Ponting, 2007). In this context, Earth system science provides powerful concepts and tools that can be used in assessing and predicting the risks to people and society of climate change and other global environmental changes, and in informing responses to these potential changes. Understanding human vulnerability in the context of these changes is as essential as understanding their biophysical dynamics.

Bringing a systems perspective to bear on these issues also allows the interplay of causes and consequences to be addressed. An iconic example of human-caused environmental disaster, often used as a warning metaphor for society's current unsustainable

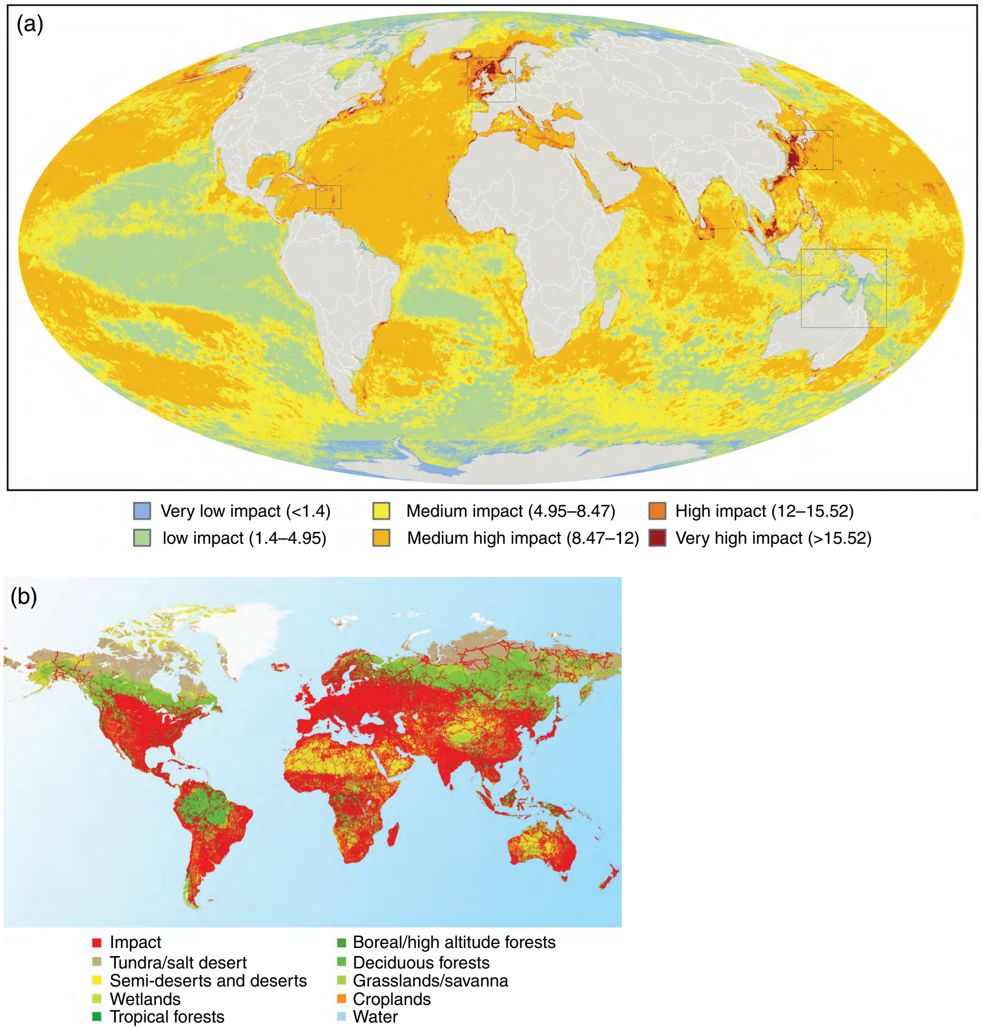

Figure 1.2 The scale of global anthropogenic impact
(a) Human perturbation of marine ecosystems This map was constructed by overlaying 17 global data sets of drivers of ecosystem change, such as fishing activity, shipping, and riverine and long-range pollution. Reproduced with permission from Halpern *et al.*, 2008.
(b) Human impact on the land environment, modelled using GLOBIO-2 (image by Hugo Ahlenius, UNEP/GRID-Arendal, 2002; reproduced with permission). The GLOBIO model (www.globio.info) makes spatial assessments of the consequences for land biodiversity of human drivers like land use, pollution and infrastructure.

situation, is the total deforestation of Easter Island in the eighteenth and nineteenth centuries, and the linked socio-political turbulence. It is also an example of the need to take a deeper and more critical look at the human dimensions of change: the balance of social science research (summarized in Rainbird, 2002) indicates that, apart from tree-felling, other, yet very familiar, human factors played a major role in the degeneration of Easter Island's society and environment. Population collapsed, and social structures with them, following contact with European explorers who introduced new diseases and destructive animals, and raided repeatedly for slaves. In Section 1.3 below, we summarize areas of social science research that are actively exploring global environmental change issues. These fields of research enable a fuller perspective to be taken, necessary to prevent over-simplification or the proliferation of modern myths of environmental threats.

The third reason for explicitly addressing human society and its activities within the field of Earth system science is that society is the *context* in which Earth system research actually happens, and where the knowledge produced is directed towards practical action. The knowledge that scientists produce will go into the public and policy domains, where it faces many possible fates: this knowledge can be debated, reconfigured and developed in the context of other fields of knowledge, and naturally it can be used in decision-making processes. Earth system science is now deeply embedded in the processes and institutions that inform society's planning for climate adaptation and mitigation, and for many other policy responses to global environmental change. This situation represents a marked change in the way that science is done and, in our view, it brings new responsibilities and challenges along with new academic insights into our Earth.

1.2 Conceptualizing the 'human dimension' from an Earth system perspective

Given the importance of people in causing and being affected by global environmental change, the research community interested in these issues faces a serious challenge: how to conceptualize and embed human agency and socio-economic context in our understanding of the Earth system.

This challenge is highlighted by a debate that has been simmering between scholars for at least 350 years. To a very large extent, a primary activity in post-Enlightenment science has been *analysis* – the breaking up of the complex world into comprehensible pieces for in-depth investigation. Established by the likes of René Descartes, whose famous maxim *Cogito ergo sum* reflected an attempt to explain the human experience rationally, by reducing it to fundamental truths, analysis through reductionism has been the basis for many (if not most) of our scientific discoveries in the modern era. This point is highlighted by futurist and social commentator Alvin Toffler (1984) who wrote,

> One of the most highly developed skills in contemporary Western civilization is dissection: the split-up of problems into their smallest possible components. We are good at it. So good, we often forget to put the pieces back together again.

Without denying the immense value of reductionist research in both the biophysical and human domains, Toffler, and many others since, have argued that to address the global challenges that face us today, the balance needs to shift back towards *synthesis*: bringing our collective perspective back up to the better-rendered 'big picture' of our world. This world is a complex world, and it is inescapable that improving understanding requires the integration of multiple perspectives. If Earth system science is to be a part of this integration process, it requires a much fuller recognition of the interconnectivity of its social and environmental components.

There have been many calls for more such integrated knowledge from environmental research funders, government bodies and the research community itself (Box 1.2), in response to the challenges posed by global social and environmental changes. The International Human Dimensions Programme on Global Environmental Change came into existence in the mid 1990s, sponsored by both the International Council of Science Unions and the International Social Sciences Council, to foster social-science research on global environmental change and to support collaborative research efforts across the social and natural sciences. In 2001, the four international global change research programmes jointly issued the Amsterdam Declaration on Global Change, which included a description of how this more integrative research should develop:

> The scientific communities of [the] international global change research programmes … recognise that, in addition to the threat of significant climate change, there is growing concern over the ever-increasing human modification of other aspects of the global environment and the consequent implications for human wellbeing. A new system of global environmental science is required. This is beginning to evolve from complementary approaches of the international global change research programmes and needs strengthening and further development. It will draw strongly on the existing and expanding disciplinary base of global change science; integrate across disciplines, environment and development issues and the natural and social sciences; collaborate across national boundaries on the basis of shared and secure infrastructure; intensify efforts to enable the full involvement of developing country scientists; and employ the complementary strengths of nations and regions to build an efficient international system of global environmental science'.[2]

Box 1.2 The current research and policy focus on 'understanding the Anthropocene'

Many organizations involved in the research process are currently orienting themselves towards better transdisciplinary integrated knowledge of global change, recognizing the importance of delivering this knowledge in a timely way to decision-makers in society in order to meet the growing sustainability challenge. This emphasis on better interaction between natural and human sciences, and on the urgency of the knowledge need, is evident at all levels – international and intergovernmental, regional and national:

- The United Nations Education, Scientific and Cultural Organisation (UNESCO) launched its Climate Change Initiative in 2009. It supports interdisciplinary integration of knowledge about climate, promoting the use of its biosphere reserves and World Heritage sites for research and implementation of climate risk management policies. A core programme focuses on ensuring that environmental ethics, social and human

[2] Text in full available on the Earth System Science Partnership website, www.essp.org/index.php?id=41

sciences are entrained in responding to climate. Also, UNESCO has designated 2005–2014 as the Decade for Education for Sustainable Development, in which climate change, biodiversity and sustainable lifestyles are key themes. See: www.unesco.org/new/en/natural-sciences/special-themes/global-climate-change and www.unesco.org/new/en/education/themes/leading-the-international-agenda/education-for-sustainable-development/about-us/.

- The International Council of Science Unions (ICSU) and the International Social Sciences Council (ISSC) identified a set of 'Grand Challenges' in Earth system science for global sustainability (Reid *et al.*, 2010). They acknowledge the huge advances made in understanding the functioning of the Earth system, but issue a call to action to researchers from the full range of sciences and humanities. The ICSU and the ISSC are also alert to the difficulties of this new mode of working, in terms of institutional structures, research methods and the incentives for participation in this evolving area. See: www.icsu-visioning.org/grand-challenges/
- The Belmont Forum is made up of representatives of funders of global change research from many countries around the world, many of which have supported socio-environmental research since questions of global environmental change first arose in the research agenda. As funders, they are influential in dealing practically with many of the difficulties that ICSU/ISSC identified in their Grand Challenges Visioning initiative. In 2011, the Belmont members made a shared commitment to supporting research that yields knowledge for action to avoid the detrimental impacts of climate change, explicitly requiring interaction of the natural and social sciences. See: www.igfagcr.org/index.php/challenge
- The IPCC itself, as the key organization providing scientific synthesis for decision-makers, has been criticized in the past for having a physical-sciences bias but, since it was formed, its reports have both reflected and shaped moves in the research community towards greater integration in order to better understand the human dimensions of global change. The Fifth Assessment Report currently being prepared puts more emphasis than any previous report on the interplay of socio-economics and biophysical changes, as well as on sustainability and risk management in the adaptation and mitigation responses. See the brochure on www.ipcc.ch/organization/organization_history.shtml
- Recognizing the strategic and practical challenges of integrated research on global change, the four global change programmes (IHDP, IGBP, WCRP and Diversitas) set up the Earth System Science Partnership to provide enabling mechanisms for the science community. It has supported joint projects on cross-cutting issues such as water, carbon, food and human health, as well as regional studies.
- In Europe, the European Commission's Research Advisory Board (EURAB) in 2004 spelled out some necessary improvements to enable Europe's research systems to better meet the transdisciplinary challenges presented by complex environmental systems (European Research Advisory Board, 2004). Its successor, the European Research Area Board envisions a 'New Renaissance', where new ways of thinking will emerge from better linkages between the natural and human sciences. See: http://ec.europa.eu/research/erab/pdf/erab-first-annual-report-06102009_en.pdf.
- The European Science Foundation (ESF) reported on its first Forward Look activity on Earth system science in 2003. That study focused primarily on biophysical changes, informing subsequent research, modelling and observation programmes (including the UK's QUEST programme). In 2009, the ESF launched a second Earth system science Forward Look, this time explicitly concerned with global change and the Anthropocene. This activity, *Responses to Environmental and Societal Challenges for our Unstable Earth*, also grappled less with the science base itself than with the need for new integrative structures and processes in research that are capable of addressing the socio-environmental issues of greatest concern. See: www.esf.org/index.php?id=6198.
- Many, many national projects and programmes have been developed recently to address the interlinked human and biophysical dimensions of global change. One example in the UK is *Living with Environmental Change* (www.lwec.org.uk), which is a multi-partner initiative involving research councils, government departments and agencies and businesses. *Nordic Strategic Adaptation Research* (www.nord-star.info) links interdisciplinary researchers across the Nordic nations with decision-makers in policy and business, and provides a model (and resources) for similar networks elsewhere in the world. *td-Net* (www.transdisciplinarity.ch) is a network for transdisciplinary research, which shares

information about methods and good practice in this frontier area of study. The *Grupo de Pesquisa em Mudanças Climáticas*, the climate change research group of Brazil's national space research institute INPE (mudancasclimaticas.cptec.inpe.br) is engaged in socio-environmental research involving multiple government, business and academic partners in Brazil and worldwide, but it also seeks to engage directly with journalism forums and organized civil society groups, and it provides a regional focus for other national research and societal engagement efforts across Latin America.

All these groups have recognized the evident need for new kinds of knowledge to equip society better for responding to the many linked challenges of global change. They have set out some institutional and operational principles for working. However, the nature of this newly integrated knowledge is still open to debate. Despite near-universal acknowledgment of the complexity of the Earth system, we still tend to deploy discipline-based approaches to the identification of the research problem. For instance, climate scientists define climate change as a physicochemical problem, the consequence of perturbed atmospheric chemistry, planetary albedo and the like. The Summary for Policy Makers of the IPCC's Fourth Assessment Report (IPPC, 2007) states, '*Causes of Change: Changes in atmospheric concentrations of greenhouse gases and aerosols, land cover and solar radiation alter the energy balance of the climate system.*' In contrast, a leading sociologist, Anthony Giddens, addressed climate change entirely as a political problem in his recent book on the topic (Giddens, 2009); while for economists, it is seen as the '*biggest market failure*' (e.g. van Ierland *et al.*, 2002; Stern, 2007). Of course, climate change is a consequence of all of these things together. The challenge remains in how we understand all of these aspects together, including their interactions.

Various tools have been proposed and tried out. Figure 1.3 shows one of the iconic conceptualizations of the Earth system, known as the Bretherton diagram. It was included in the NASA-sponsored Bretherton Report, *'Earth System Science: A Closer View'* (NASA Advisory Council, 1988), which set out a scientific research agenda for the emerging field of Earth system science. The Bretherton Report was profoundly influential. The development of Earth system models in the period since it was published can be seen as the progressive inclusion of sub-models representing the different boxes and arrows in the diagram, drawing on the findings of many international collaborative research programmes for biogeochemistry and climate science.

The figure shows how scientists viewed the Earth system as a set of interactions between the physical climate system and the biosphere mediated through various global biogeochemical cycles. The dynamics of the system are 'forced' by energy changes associated with natural variations in solar intensity and with the reductions of incoming solar radiation reaching Earth's surface caused by volcanic eruptions shooting ash and sulphate aerosol into the upper layers of the atmosphere. People feature in this diagram as a semi-external forcing on an intricately coupled biogeophysical system. Human activities cause land-use change and are a source of CO_2 and pollutants. These human activities are clearly affected by climate change and dependent on (land) ecosystems.

The Bretherton diagram was an important first step in demonstrating the links between human activity and environmental processes. Overall, however, people were not presented in this approach as being a fully endogenous part of the system. In this framework, the few elements representing all human activity contrast sharply with the more richly resolved processes of the natural world. This asymmetry has been reflected in research investments and international research infrastructure in the area of global environmental change until comparatively recently.

Social research at the global scale emerging at around the same period reflected these growing concerns about societal and environmental change linked to globalization and economic development. The priority research questions articulated in the late 1980s still look very topical today, but they do not fit easily into the Bretherton schema:

> What are the persistent, broad-scale social structures and processes that underlie these changes? In particular, what are the relative roles of the amount and concentration of human population, the character and use of technology, the changing relation between places of production and consumption, and the 'reach' and power of state and other institutional structures? How does the relative importance of these roles for environmental change vary across cultures, and through history? (SSRC, 1988, cited in Clark, 1988)

These questions involve structures, processes, changing dynamics, and causalities – all terms common to systems analysis and familiar to Earth system scientists, but they also address important social concepts, such as power, culture and institutions, that

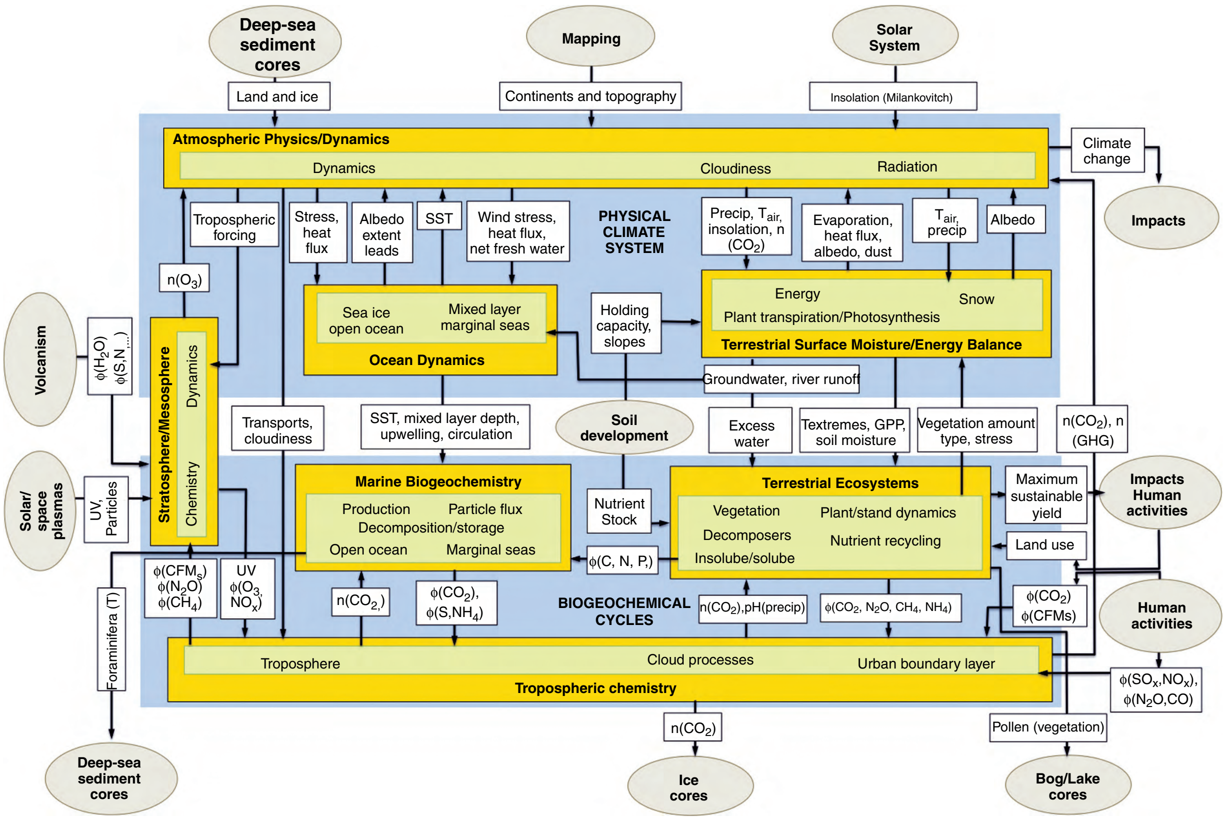

Figure 1.3 The Bretherton diagram (redrawn with permission from NASA; original figure published in *Earth System Science: A Closer View*, Report of the Earth System Science Committee of the NASA Advisory Council (1988), pp. 29–30).
This conceptual model, developed as part of a strategic research plan by the Earth System Science Committee of the NASA Advisory Council, represents Earth system processes occurring at timescales from decades to centuries. The ovals show exchanges with the external environment, or processes that operate over much longer timescales. The arrows connecting the sub-systems represent quantifiable measures that can be included in Earth system models. Contemporary Earth system models now include most of these processes.

do not translate well into quantitative measurements or computer models. Thus, research exploring these issues developed alongside the biophysical and climate studies, despite the recognition of the inextricable link between human development and the natural environ- ment. Gro Harlem Brundtland, the chair of the World Commission on Environment and Development, wrote in the foreword of *Our Common Future*, the Brundtland Report (1987): 'Environment *is where we all live; and* development *is what we all do in attempting to improve our lot within that abode. The two are insep- arable*'. Yet in terms of the research that has informed environmental and development policy, and the fram- ing of the research questions, the social and natural sci- ences have largely followed separate paths.

Many still regard the complexity and the inter- disciplinarity of the research effort now needed as an enormous challenge. The Bretherton diagram is a representation of the Earth system from a physical- sciences perspective. It has been a very important visualization of a set of priority areas for research into environmental and climate processes, but there is a growing discussion in the global change research com- munity of the limitations of thinking of the Earth sys- tem in this particular way. Major questions for today's Earth system scientists are how far we have progressed from Bretherton's early conceptualization, and whether and how human activities might be better represented using the next generations of models. '*Structuring sup- port for human dimensions research only around themes defined by natural science is inadequate*' (as stated by the Human Dimensions of Global Environmental Change committee, NRC, 1999, p. 62), but what might a consideration of the key processes and interconnec- tions look like from other perspectives? In particular, what can now be gained in terms of understanding the Earth system if it is viewed from more than the just the physical-sciences perspective? This effort must draw on the existing knowledge resources available in a wide range of disciplines, so the focus is increasingly on the 'integration' of knowledge, in ways that accommodate the multiple perspectives and insights from these different fields.

1.2.1 Towards an integrated understanding of the Earth system

The physical-sciences community has been making the most visible and vocal calls for the wider engagement and entrainment of knowledge from other fields, in large part because of the increasing demand for scientific insights to inform policy on climate and global environmental change. The changing interaction between Earth system science and policy is explored more fully later in this chapter; for now, the point is that Earth system science has recognized some important limitations in the deployment of its outputs in the real-world context, with many of these constraints relating to its interface with the human sciences. This recognition is what drives the desire to expand the scope of the field.

However, the methods and approaches of Earth system science are seen by many scholars in other fields as not entirely fit for these purposes, without some kind of transformation. In the view of many social scientists, Earth system science has followed a scientific tradition based on the search for universal laws and principles. In fields with more descriptive and interpretative traditions, there is a concern that the dynamics of the planet and its human inhabitants cannot be adequately described by reductive analysis of the components. Fortunately, many disciplines – and 'interdisciplines' – have well-established approaches to understanding the complex dynamics of a changing world that Earth system science can combine and draw upon.

Another well-debated theme from the social sciences that is beginning to resonate in contemporary Earth system science is their intensely critical concern with how the position of the researcher influences the outcome of the research.

For example, Demeritt (2001) explores the tacit social, cultural and political commitments of climate science, which shape the ways in which particular issues are defined as worthy of research, and determine the methods and techniques for the research inquiry itself. He argues that there is a tendency to '*concentrate upon the uses of scientific knowledge "downstream" in the political process*', and '*discount the ways in which a politics – involving particular cultural understandings, social commitments, and power relations – gets built "upstream" through the technical practices of science itself* (p. 306). The risks arising from this situation, where embedded assumptions and judgments are not acknowledged, include the messy battles of climate skepticism, opacity in what should be democratic processes of decision-making, and, Demeritt suggests, the problem that people simply are turned off by an overly technical and globally undifferentiated scientific line, precisely when there is a need to engage the global citizenry fully in the societal changes that are needed. The response to public doubts and scientific uncertainty is not merely to provide more and more technical knowledge about the Earth system. There is also a pressing need to recognize, reflect upon and work with the social context of this science, to build the social trust and solidarity that are needed for any effective response to the challenges.

Hulme (2008) explores a different perspective, but also one that is a major concern for social scientists dealing with environmental change: the fact that climate means different things to different people in diverse cultures. He argues that climate needs to be conceptualized and presented as a '*manifestation of both Nature and Culture*'. From this starting point, it follows that scientific insights about climate change, although it is a global phenomenon, need to be communicated at the level at which they are experienced: in terms of local weather, and also of how that weather relates to local environments and cultural practices. Like Demeritt, Hulme also gives pause for thought about the position of power – in academic and policy debates – of physical climate science. The failure consciously and deliberately to recognize the cultural context and dimensions of Earth system science means its research products can be appropriated by any of a growing range of ideologies when they are channelled into the policy process: '*Climate change becomes a malleable envoy enlisted in support of too many rulers*' (Hulme, 2008, p. 10). Hulme also points out that the language of the natural sciences, with their complex models, graphs, maps and so on, has more power – what he calls universality and authority – than the generally more context-dependent and context-specific findings of the social sciences, resulting in a narrowed climate policy agenda that excludes other approaches.

Both Hulme (2008) and Demeritt (2001) address the context in which more integrative research is needed, but the *content* of this research is also a focus of debate. At times, it can feel like an impasse between the different methods of the human and physical sciences. The debate is often framed rather bluntly in terms of the contrast between the physical science's focus on quantifiable and generalizable laws about objective phenomena, and the social sciences, where approaches are frequently less concerned with identifying general causalities, but instead can be narrative, interpretative or idiographic, seeking out the idiosyncrasies and specificities of a situation as a means of arriving at an in-depth understanding. In reality, the current situation in global change research is not so simply polarized: many areas of the social sciences have rich traditions of quantification, including the definition of precise formalisms, and of the identification of 'social mechanisms'. Causal relationships can be investigated 'scientifically' in the human domain, just as in the natural world. And Earth system science is not a rigid framework of the immutable laws of physics; its methods and approaches are supposed to allow the investigation and understanding of complex causalities, contingent behaviours, adaptive responses, and a wide range of other interdependencies, including those between the human and natural domains.

1.2.2 Current approaches to integration

We can now see a continuum of efforts for this integration in global change research, ranging from 'meeting in a conceptual middle', mediated by a shared set of tools and approaches in which modelling plays a key part, through to a 'rich-portfolio' approach that is more focused on the process of knowledge production and sharing, including dialogue and reflexivity. Before we move on to explore the key social, economic and policy concerns in contemporary global change research, we will describe some of these approaches to integration more fully.

Impacts modelling

One active area of development in Earth system science involves the inclusion of more processes and connections within existing Earth system models. This more comprehensive simulation, together with rapidly improving spatial resolution in the models and techniques for scaling down from global to regional and local scales, allows for a more robust assessment of the interactions among climate, vegetation and hydrology, and other domains. This improved understanding in turn provides invaluable insights to questions about future water supplies, crops, some environmental hazards – and hence projected impacts on human society. This area of research is a key theme in later chapters of this book.

The steadily expanding scope of mainstream Earth system modelling increasingly looks towards processes relating directly to human activities. Since the early years of global change research, human activities and impacts have been flagged as important Earth system processes, but they have also been comparatively under-specified. The Bretherton diagram of physical and biogeochemical processes maps conceptually and structurally onto the Earth system models and Earth observation programmes that have subsequently and progressively been developed. At the time that the Bretherton Report was published, the human dimensions research community noted the power and value of having such an over-arching representation of their research fields, '*to convey visually the interconnections among diverse cultural, economic, political, social and institutional phenomena and to begin to relate these theoretically*' (Balstad Miller and Jacobson, 1992, p. 175). Figure 1.4, known as the Social Process diagram (Kuhn *et al.*, 1992), was drawn up by the Human Interaction Working Group of the Consortium for International Earth Science Information Network (CIESIN), prompted by and developed in response to the Bretherton diagram, with these objectives in mind.

In the last two decades, the international human dimensions research agenda (as outlined, for example, by the IHDP (2007) and its previous strategic plans) has indeed been shaped broadly around the diagram's set of driving forces relating to the interactions between human activities and global environmental change. However, this diagram has not developed into a social science modelling and observation programme that slots seamlessly into the 'human activities' box of the Bretherton diagram. This is at least in part because of the very great diversity within the social sciences, in terms of concepts, theories and methodologies. The requirements in Earth system modelling for categorization and the fixed (quantitative, computational) representation of causal processes do not marry well with many of the fields of social inquiry. Another obstacle to wider social science engagement with this approach is that our impacts models make the same mistake as the tradition of environmental determinism, namely that they embed an assumption that all the world's societies react in a similar way to environmental conditions. Later in this chapter, we explore potential developments in this area.

Integrated assessment models

Modelling that combines scientific and economic aspects of global change is one area of integration that already has a very well-established track record. Integrated assessment models (IAMs; Figure 1.5) are

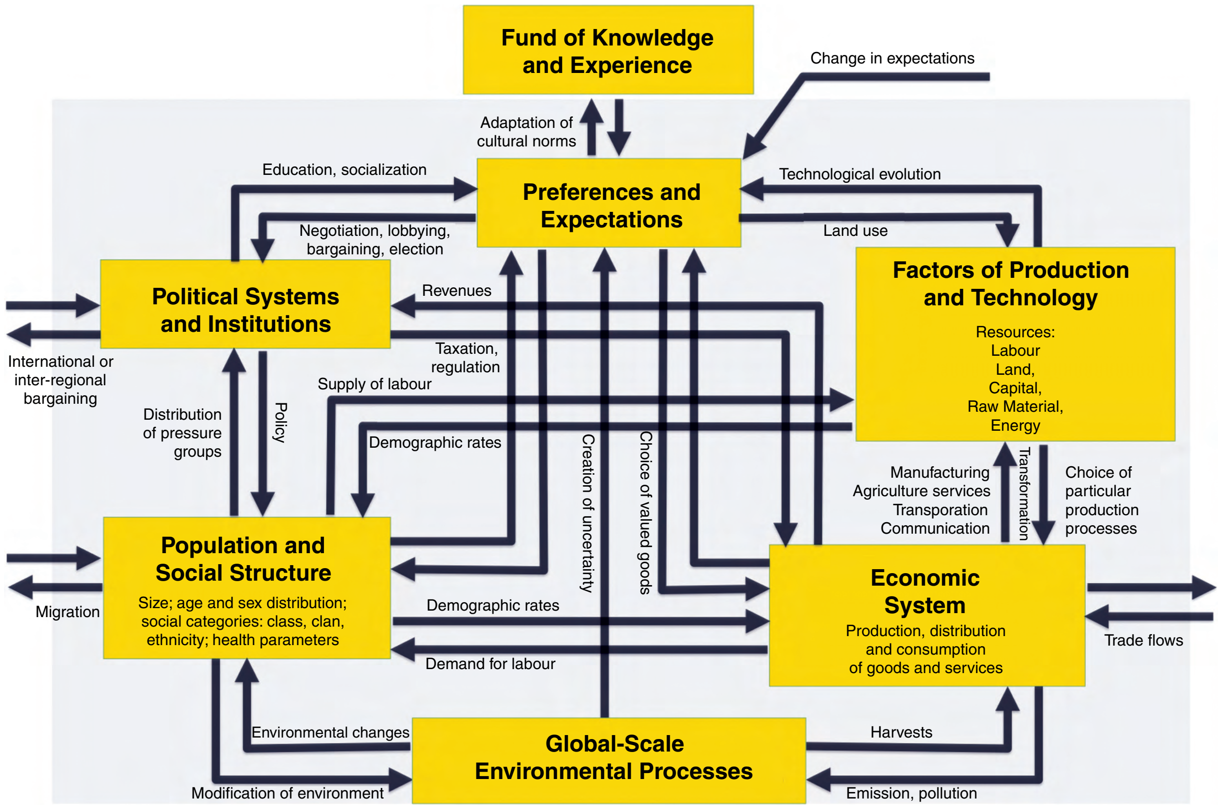

Figure 1.4 The Social Process diagram (redrawn with permission from CIESIN; original figure published in Kuhn *et al.* (1992) *Pathways of Understanding: The Interactions of Humanity and Global Environmental Change.* University Center, MI: The Consortium for International Earth Science Information Network, pp. 32–33).
This diagram developed from discussions of the Human Interactions Working Group of CIESIN, which had been funded by NASA to forge a link between the natural and social sciences in the context of global change research. The diagram represents the human system as a structure consisting of seven 'building blocks' connected by driving forces of change.

designed to explore or optimize policy options, and have been developed for a wide range of contexts where the interactions of technology, environment and the economy have societal consequences, including air pollution, land-use change, energy security and so on. They underpin contemporary climate change science and policy because of their application in the development of quantitative scenarios of potential future emissions of greenhouse gases (e.g. the SRES scenarios described in IPCC, 2000; and the new scenarios for the IPCC's Fifth Assessment Report based on Representative Concentration Pathways outlined in Moss *et al.*, 2010). Among the earliest integrative efforts of this kind were the Club of Rome's global models used in *World Dynamics* (Forrester, 1971) and *The Limits to Growth* (Meadows *et al.*, 1972), which linked representations of population, natural resources, the economy and pollution, with an explicit intention to '*clarify the course of human events in a way that can be transmitted to governments and peoples*' (Forrester, 1971, cited in Meadows *et al.*, 1982). By the 1980s, several different models of different types, complexity, underlying methodologies and purpose had been developed worldwide to address issues like energy, food security, and environmental change, and a long-standing series of symposia for information exchange on the developments in global modelling had been established by the International Institute of Applied Systems Analysis (Bruckmann, 1981).

In their delightful and thoughtful reflection on the first decade of global system modelling, Meadows *et al.* (1982) made the perhaps obvious point that '*as long as there are global problems, there will be a need for global models*' (p. xxiii). Nevertheless, they recognized the profound methodological challenges required to increase the understanding of the '*complex, interlocking, interdisciplinary sorts of issues*' that typify global environmental change. Many of these methodological challenges still remain. Kelly and Kolstad (1999) have reviewed IAMs in the climate context, explaining their

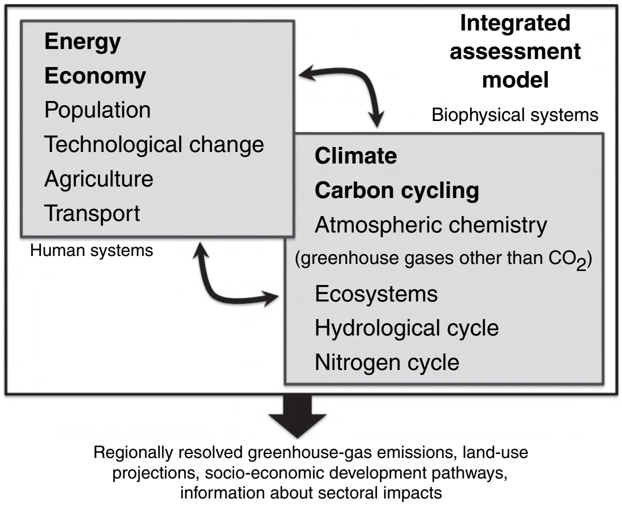

Figure 1.5 A generic representation of integrated assessment models.

assumptions and applications. Tol (2006) explains the challenges of integration in terms of issues in model coupling. Janetos *et al.* (2009) present a perspective on recent developments in integrated assessment modelling, arguing that IAMs are evolving towards the structural comprehensiveness and simulation capability of Earth system models. Much of the literature relating to IAMs focuses on issues of uncertainty (e.g. Visser *et al.*, 2000; Mastrandrea and Schneider, 2004; Tavoni and Tol, 2010). Uncertainty in integrated modelling arises from the necessarily simplified models of both the economy and the environment that are combined in these models; the assumptions made about the drivers of change, and about the nature of the relationship between the economy and the environment; the quality of the data available for input to the model; and increasingly – as models are used in more predictive ways, rather than as heuristic, exploratory tools – the variability of model output and the divergence between models. Different approaches are needed for the assessment and management of the various dimensions of uncertainty. Adding to the challenge, the linking together of very different kinds of model in integrated assessment modelling mean that multiple kinds of uncertainty are at play, and they are not always teased apart for systematic attention, despite concerns that IAMs should not be 'black boxes' (Kelly and Kolstad, 1999). Ackerman *et al.* (2009) set out some of these methodological concerns. In particular, they '*maintain that IAMs enjoy an epistemic status different from their natural science counterparts, and that economic models mix descriptive analysis and value judgments in ways that deserve close and critical scrutiny*' (p. 299).

Transdisciplinary inquiry

The critical scrutiny of methodological and theoretical aspects of research is arguably the distinguishing characteristic of the social sciences. Ironically, this may well have been a significant part of the barrier to interdisciplinary working and knowledge integration in global change research over recent decades: it marks a sharp contrast with most natural science, which stakes its claims on 'objectivity', designing its methods around an ideal of independence from context, values and world views. Gilbert and Ahrweiler (2009) explore this difference in depth, reviewing the philosophical and historical reasons why the social sciences have generally not focused on simulation modelling for their research questions. Because the ultimate theoretical interest in many of the social sciences is the individually significant, contingent and particular aspects of human experience and social reality, the starting point for integration with Earth system science, with its emphasis on systematization and computer modelling, was initially a very small potential intellectual meeting ground. The growing focus on the environment in the social sciences and humanities (ISSC, 2010) is now expanding the scope for integration across disciplinary divides.

This expansion of collaborative, transdisciplinary working is also now opening up debates about what constitutes 'good' integrated research and knowledge, and how it should be carried out. Brown (2009) points out that these debates are '*not essential for the conduct of outstanding research, as long as the researcher is either lucky, highly instinctive, or able to slavishly follow a suitable model from previous work*'. Many people, in both the natural and social science communities, are now arguing strongly that research into a dynamically changing world, that bridges disciplines and, most importantly, informs real-world decision-making, falls into the category of research that requires close and critical scrutiny at all its stages. There are many terms for these debates, reflecting their emergence in various different fields of research. *Transdisciplinarity* is a useful overarching term; it carries within it the notions of bringing together empirical knowledge from different contributing disciplines, addressing questions that may well lie beyond the scope of any one individual discipline, and being directed to some purposive action in a real-world problem situation. There is a growing consensus (e.g. Thompson Klein *et al.*, 2001; Max-Neef, 2005;

Pohl, 2010) that this kind of research should engage actively with the stakeholders involved in and affected by the problem or research question, and this in turn prompts the growing focus on values and responsibilities in research that we have already mentioned. Other related areas include *post-normal science* (e.g. Funtowicz and Ravetz, 1993), which focuses on the democratic dimensions of how to deal with situations where there is a high degree of system uncertainty and the decision stakes are high, and '*Mode 2*' *science* (e.g. Gibbons *et al.*, 1994; Nowotny *et al.*, 2003), which emphasizes the process of co-development of knowledge between academics, practitioners, and other stakeholders, particularly considering the institutional and epistemological changes that this form of societally engaged research requires. A common theme in these debates is the attention they give to the role of the citizenry in science and environmental governance, and their emphasis on transparency and accountability in science, particularly when knowledge from different specialist fields needs to be combined in order to present a more integrated picture of a complex world.

These debates may not have radically transformed the content of Earth system models, but they are increasingly influencing the way in which Earth system models are deployed in the policy context, and the way that Earth system research is being designed at a strategic level (Section 1.4). Nevertheless, it is important to recognize the extent and depth of academic concerns, particularly in the social science research community, about the process and approaches for the integration of knowledge. Debates about methodologies are taking place together with a more explicit questioning of the underlying assumptions in socio-environmental research, and there is often a tangible tension in meetings and in the transdisciplinary academic literature. In the context of global change, knowledge needs are urgent, but sensitive and supportive approaches to research integration are nevertheless needed.

'Integration of knowledge' from the social and natural sciences is in many ways an effort to square a circle, which unsurprisingly presents persistent problems. Disciplines can be regarded rather like cultures, characterized by their shared language and practices (Strathern, 2006). As with any encounter between long-established cultures, efforts at interdisciplinary engagement can be hampered by profound and sometimes bewildering differences in behaviours and motivations. Where one knowledge culture is dominant – as is currently the case for the quantitative sciences (e.g. Demeritt, 2001; Bjurström and Polk, 2011), there is even greater sensitivity around efforts to integrate or assimilate the outputs of scholarly inquiry. There is often a tacit presumption that integration for Earth system science is merely a question of quantifying the qualitative, but many social scientists argue emphatically, like Gilbert and Ahrweiler (2009), that '*the social sciences are not a 'pre-science' waiting to approximate the state of the natural sciences via more and more discovery and mathematisation of the laws of the social realm*'. The early social theorist Weber described where law-finding strategies could be useful (e.g. Weber, 1988; p. 12ff), but argued that they need to be complemented with detailed investigation and description in order to provide the requisite knowledge. Nevertheless, recurrent assumptions about social science and the role of social scientists continue to appear in the '*… sometimes colonising and patronising rhetoric of "good science"*' (using the words of Gilbert and Ahrweiler again), and they need to be recognized and confronted when they appear (Box 1.3). Steady progress is being made in bringing together the best available knowledge from all disciplines to inform responses to global change, but for the time being it is still vital to bear in mind that '*for interactions between the social and earth sciences to succeed, a certain level of tolerance and mutual understanding will be needed*' (Liverman and Roman-Cuesta, 2008).

Box 1.3 Debunking myths about human dimensions research

- Humans matter in global environmental change …
- … And not just because of population pressures
- Human behaviour may not be predictable …
- … And predicting even the predictable human behaviour may not be socially desirable
- Economists are not the only social scientists that are needed
- Social science is *science* – not politics or journalism
- Social scientists are smart enough to understand equations
- Social scientists can do large-scale research
- Social science is not always cheaper
- Social scientists can help with stakeholder engagement
- Social science may enhance the chances of environmental research being relevant, and of getting funded.

(Adapted with permission from presentations by Diana Liverman.)

Perhaps a more serious concern than the potential intellectual sensitivity of scientists in the interdisciplinary fray is the fact that the divisions of academic life into disciplines have resulted in a discouragement to asking questions that require combining modes of investigation that may be derived from more than one discipline, or even in developing fundamentally new modes and new conceptualizations. So for example, we still face huge gaps in understanding climate adaptation from a practical, policy-relevant point of view, in part because until recently it has not been in the interest of any (discipline-bounded) kind of academic to study it.

Promising new areas for transdisciplinary integration include the conceptualization of society and the natural environment as a linked, mutually adaptive system, recognizing the complexity of the interactions between humans and the natural world. These new approaches bring prospects of entraining knowledge from very diverse fields; most scholars now agree that understanding global change over multiple scales of space and time involves historical and cultural and even philosophical perspectives in addition to the biological, physical and (geo)chemical. Wittrock (2010) emphasizes the need to take a critical, reflective view on these integrations:

> It is a great challenge for the future to maintain and strengthen intellectual sites in research and academic landscapes which are both open to cooperation across the divide between the cultural and the natural sciences and yet characterized by a measure of organized scepticism against proposals that entail that the social and human sciences should rapidly abandon core elements of their own theoretical traditions.

In the next sections, some of these 'core elements' are outlined, for the social sciences, economics and policy studies. It is not our objective, even if it were possible, to present a comprehensive review and meta-analysis of these fields of study. (Suggestions of some books that provide fuller treatments in these areas are given in Box 1.4.) In each case, a few seminal issues or areas of research have been selected to illustrate the corpus of research on human dimensions of global change. The basis for the selection is either that the dialogues for integration in Earth system science are already mature, or that there are particular areas of debate or controversy that currently impede the integration of knowledge.

Box 1.4 DPSIR – a simple systems framework in practice?

Humans causing damage to their environment also ultimately cause damage to themselves as a result of being part of that degraded environment. At the practical level, many decision-makers involved in real-world responses to socio-ecological problems use the Driver–Pressure–State–Impact–Response framework for analysing the cause–effect behaviour (DPSIR; OECD, 1993; EEA 1999). Unlike environmental impact assessments, which attempt to identify and quantify the impacts on the natural environment of human activities (development), and risk or hazard assessments, which identify and quantify the consequences for people of a given environmental change, the DPSIR framework (see Figure 1.6) allows for the conceptual analysis of interactions in both directions, on multiple scales and indeed over a cyclic or recurrent process of changing human activities and changing environment.

The DPSIR framework highlights that effective responses may need to tackle issues at the multiple levels. Remediation of the state-change evident in the environment is one level, but response options also include interventions to reduce the impacts felt by society, changing sector policy and the behaviour of members of society. Contexts where the framework has been used extensively include coastal-zone management, the delivery of aid programmes and, increasingly, in global-scale changes. The analysis reported in the Millennium Ecosystem Assessment (2005) was structured in this way. The outline for the forthcoming Working Group 2 contribution to the Fifth Assessment Report of the IPCC differs from previous assessment reports in being more oriented towards adaptation options in a state–impacts–response framework.

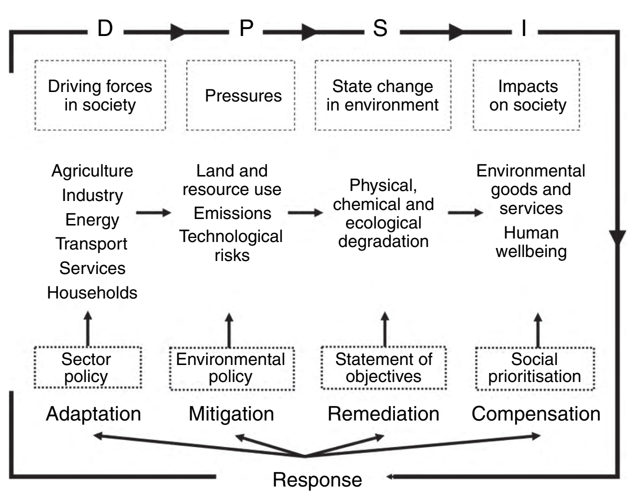

Figure 1.6 The DPSIR framework.

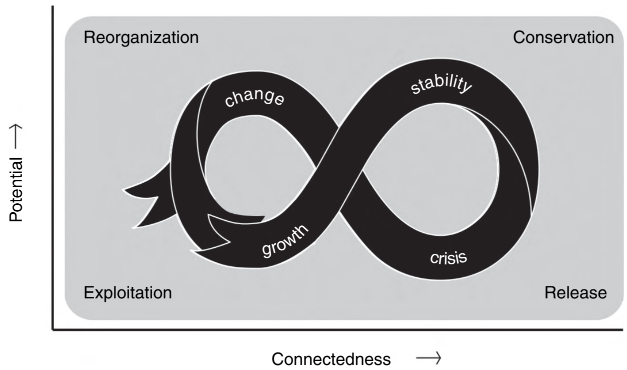

Figure 1.7 The resilience cycle in socio-ecological systems. Adapted from the panarchy model of Holling and Gunderson (2001).

1.3 Social science perspectives on the Earth system

1.3.1 Social science priorities

In order to map out the scope of contemporary social sciences and identify the key areas where research priorities are aligned with the interests of Earth system science, we have turned to two international bodies that represent social scientists' interests and shape research strategies and agendas. The first of these is the UNESCO-supported International Social Sciences Council (www.worldsocialscience.org), which highlighted several global challenges in its 2010 World Social Science Report (ISSC, 2010). The second is the IHDP, which has an explicit remit to frame worldwide social science research within the context of global environmental change (IHDP, 2007).

Both these international bodies emphasize the essential importance of the contributions social science can make in understanding societal trends and overcoming global challenges:

> Research conducted under the auspices of IHDP is predicated on the premises that global change research should address major social and economic science concerns, shape a social science of global change, and contribute knowledge to meet a number of major challenges currently facing societies (IHDP, 2007; p. 4).
>
> The social sciences are concerned with providing the main classificatory, descriptive and analytical tools and narratives that allow us to see, name and explain the developments that confront human societies. They allow us to decode underlying conceptions, assumptions and mental maps in the debates surrounding these developments. They may assist decision-making processes by attempting to surmount them. And they provide the instruments to gauge policies and initiatives, "and to determine what works and what does not" (ISSC, 2010; p. 9).

The lists below show the priority strategic issues that the IHDP and ISSC have identified. Several of them have an intrinsic environmental dimension; mutual gains in knowledge – and a better-founded expectation of overcoming the real-world challenges – can arise from interaction between social scientists and natural scientists. For other issues (such as social learning, institutions, equity), Earth system science may not be geared towards contributing to those bodies of empirical or theoretical knowledge, but it can still engage with them and draw from them in the effort to better understand global changes. Gudmund Hernes, President of the ISSC, called for this broadened engagement, issuing '*a plea for integrated research where the humanities and the natural and social sciences jointly address natural phenomena, social processes, institutional design, cultural interpretations, ethical norms and mindsets*' (ISSC, 2010; p. ix).

ISSC global challenges:	IHDP cross-cutting themes:
• global environmental change • poverty • equity, inequalities and the global economy • population and demographics • social unrest and violence • urbanization	• vulnerability, adaptation and resilience • governments and institutions • social learning and knowledge • thresholds and transitions

1.3.2 The shared language of systems

Understanding the social phenomena listed above requires understanding not just of social structures but also of social processes. These might include cooperation, conflict and the myriad transactions between social groups. This process orientation in the social sciences is shared with Earth system science, and offers one point for intellectual convergence between these disparate academic fields. But how can we understand the 'dynamics' of individuals, institutions, communities and society?

An immediate challenge is that there are many very different schools of thought within the social sciences, bringing sharply different theoretical perspectives to the questions of social structures, processes and capabilities for bringing about social change (often termed 'agency'). Indeed, the theme of the 2010 ISSC report (p. 3) was '*knowledge divides*', acknowledging the difficulties that this multiplicity presents, but also framing this diversity as an asset: it potentially offers a much richer picture of humans and their social interactions. Many fundamental social theories have addressed human society within the natural environment to some extent. The most important factor in a social phenomenon might be evaluated very differently by these different perspectives (e.g. Goldman and Schurman, 2000).

It is important to look back at the experiences and, in some cases, the pitfalls of these various approaches as we seek to develop new integrative approaches. Table 1.1 shows examples, in cartoon outline, of several social theories that have dealt with nature–society interactions, using the links between climatic changes and famine to illustrate the kinds of causal explanation that these different fields proffer. These examples have been selected not because they are broadly representative of all the social sciences, but because they are some of the socio-environmental discourses that have been influential beyond the academic field, and that continue to be debated now.

Within the various approaches in the social sciences, there are also very different, and often contested, ways of understanding social processes. Some theoretical framings have been oriented towards describing the dynamics of society through the identification of direct causality. Underpinning these framings is the view that a social phenomenon can be explained in terms of cause/effect relationships, which can be subjected to the same kind of scientific investigation as is used in the natural sciences (e.g. Outhwaite, 1998). The focus of these fields of study, rather like the natural sciences, is the 'mechanism', and their ideal endpoint is the abstraction from observed cause/effect relationships into generalizable laws about society and social processes. For example, both Malthusianism and environmental determinism tend to take this kind of positivist, reductive stance. Broadly speaking, these social theories were most prevalent in the past, and have largely been discredited, falling out of favour in the latter half of the twentieth century. However, causality and mechanism are again rising in the discourse of the mainstream social sciences (a sample of the debate can be seen in Hedström and Ylikoski (2010) and Abbot, 2007) and in philosophy of social science (e.g. Bhaskar, 1998). This is in part because of the growing academic attention to knowledge *for action*, where the goal of science–policy interaction is to deliver evidence for interventions in society. This goal drives a demand for predictive power in the findings of social theory, which mirrors and is reinforced by the same demands of the natural sciences. Global change research is the impetus for a major strand of integrative socio-environmental research that leans towards more 'mechanismic' naturalistic approaches (seeking 'how–possibly' explanations), if not necessarily mechanistic ones (that provide actual causal explanation). This includes work on impacts assessment and the development of quantitative socio-economic scenarios for use in climate change modelling.

For many other fields in the social sciences, giving an adequate account of a social process or phenomenon means providing as full and coherent as possible an explanation, rather than necessarily seeking to identify the causal mechanisms (that is, by eliminating alternative possible causes) and providing predictive power. What constitutes explanation is itself a long-standing debate in the social sciences. In an early but still sound contribution to the debate, Jarvie (1964) gives examples of the kinds of explanation that might be deployed for social events. To 'explain' a lynching, for instance, he notes that a social scientist might trace the origin of the habit of mobs summarily executing prisoners; investigate the intentions of the participants in the mob; note the particular dispositions in certain regions at certain times for this kind of dispensation of justice; identify the reasons for an individual's participation in this particular lynching; consider the 'social function' of such events (which is in part an explanation of the practice in society in terms of its effects, rather than its causes); assess the extent to which a description of an event fits pre-existing theory; and of course make empirical generalizations (*'all lynch mobs get out of control*').

Jarvie's vignette shows several features of social explanation that present challenges to those seeking greater integration in global change science. First, for the vast majority of social research, explaining social events and phenomena is not a simple process of eliminating 'false' causes through experiment or observation and narrowing down to the 'true' one. The objective of the research is often precisely to obtain a richly textured and fine-grained picture. Where social events or mechanisms have a multiplicity of causal processes acting in conjunction, the outcome – and the explanation – will be contingent on all those contributory processes. This is a feature of complex

Table 1.1 Examples of different theoretical framings applied to the same socio-environmental phenomenon
This table shows why adaptation, vulnerability and impacts research follows different strands, and also why social scientists hold some deep-seated concerns about quantification of human and social phenomena. This table has been developed from a list of different social science framings first devised by Diana Liverman.

Theory: key features	Explanation of causal sequence	Current debates
Malthusianism		
Malthus (1798) argued for the need to control population growth or face a 'positive check' (warfare, disease or other catastrophe) as population returns to sustainable level.	Climatic changes *cause* population growth beyond carrying capacity *causes* famine	Does population growth need to be tackled? '*Failing to confront adequately questions of social scarcity, or confused regarding whether the scarcity in question is social or natural in character . . . is a mistake.*' (Shantz, 2003); '*We . . . alerted people to the importance of environmental issues and brought human numbers into the debate on the human future.*' (Ehrlich and Ehrlich, 2009)
Environmental determinism		
The idea that physical environment determines cultural development was prominent in the late nineteenth/early twentieth centuries (e.g. Huntington, 1913). It was strongly discredited by the mid-twentieth century, for its conflation with racism and imperialism.	Climatic changes *cause* reduced crop yields *cause* famine	Where will the 'winners' and 'losers' be in climate change? '*The current global environmental crisis is now so severe and pressing that . . . the deterministic role of the environment is relevant again. . . . This environmental determinism distorts realities as well as results in unintended consequences, frequently with negative impacts on the least powerful.*' (Radcliffe *et al.*, 2010)
Cultural/human ecology		
Features of social organization are explained in terms of interacting ecological and social historical factors (e.g. Sauer, 1925; Steward, 1955). The field has a strong focus on process (adaptation), and also on the fusion of the ideas of ecology and the human sciences.	Climatic changes *cause* adaptive responses shaping social organization *cause* changed agricultural systems *cause* famine	How can the conceptual division of society from 'external' nature be overcome? Descola and Pálsson (1996) reviewed the field, '*emphasising the problems posed by the nature–culture dualism, some misguided attempts to respond to these problems, and potential avenues out of the current dilemmas of ecological discourse.*' Head (2007) sets the debates in contemporary context: '*It is precisely because of the pervasiveness of human activity that we need to critically re-examine the work that the metaphor of 'human impacts' is doing. Human impacts is a hard-won concept that has made a crucial contribution to our understanding of the long-term human role in earth processes. Yet . . . it is neither conceptually nor empirically strong enough for the complex networks of humans and non-humans now evident.*'

Theory: key features	Explanation of causal sequence	Current debates
Mainstream (neoclassical) economics		
Key elements of theory are rational actors, basing allocation decisions under conditions of perfect information to maximize utility, with the system achieving equilibrium between supply and demand. The founding thinkers in this large and hegemonic field include Adam Smith, William Stanley Jevons, Maynard Keynes and Milton Friedman.	Market demand *determines* factors of production (in part subject to climatic changes) *determine* supply *determines* price *causes* decline in food availability *causes* famine	Are markets the best – or only – approach for managing the global environment sustainably? '*An effective, efficient and equitable collective response to climate change will require deeper international co-operation in areas including the creation of price signals and markets for carbon.*' (Stern, 2007) '*The debate over whether and how environmental economists ought to measure noninstrumental and nonanthropocentric values, such as the worth of a plant unseen by and of no apparent use to humans, will not be settled soon.*' (McAfee, 1999)
Political economy/political ecology		
Social, political and economic conditions are seen as the dominant determinants of the consequences of environmental changes. A key concern in this field is understanding and illuminating power relations that shape access to resources (e.g. Blaikie and Brookfield, 1987).	Poverty *causes* vulnerability (to climatic changes) *causes* famine	Who is responsible for the climate problem, and who should respond to it? '*What counts as nature and what works as nature politics are two arenas that are being effectively remade.*' (Goldman and Schurman, 2000) '*Starting with* a priori *judgments, theories, or biases about the importance or even primacy of certain kinds of political factors in the explanation of environmental changes, self-styled political ecologists have focused their research on environmental or natural resource politics and have missed or scanted the complex and contingent interactions of factors whereby actual environmental changes often are produced.*' (Vayda and Walters, 1999)

systems: even if the 'initial conditions' were able to be identified and well specified, determining the covering laws for social processes remains an impracticable task. Without venturing into the rich philosophical debates on this topic, Bhaskar (2008) emphasizes that causality includes both the antecedent conditions that trigger mechanisms, and the mechanisms themselves. This sets a phenomenon or event into a specific context; understanding the event entails understanding that context.

In addition, whereas functional explanations (that is, those that explain a structure or phenomenon in terms of what it *does*) predominate in natural science, many explanations of human action relate to human intentions, or human choice. In these cases, the outcome is 'contingent' upon a future goal or end at which the action is directed, not just on the past stages in the process leading up to the event. In many social scientists' view, that intentionality puts a kink in the 'arrow of time': history is not and cannot be a simple predictor of the future.

Another major challenge for integration relates to the way in which knowledge is acquired about social phenomena. The scholar's cognitive interests influence the structure of the explanations sought and made (for instance, in terms of one of the theoretical framings described in Table 1.1). The conditions under which knowledge is acquired provide a particular context to each inquiry. More importantly, the interpretation of this context by the scholar is a vital dimension of some fields of the social sciences. From this perspective, the understanding of social interactions, in the present and in history, depends on the meanings that people attribute to their actions, to their social context and, indeed, to the natural environment.

The complex causalities and the interdependence of the system in question with its context both suggest that a systems-oriented research approach is needed for an integrative understanding of global change. In the systems approach, the system – a part of reality – is conceptualized in terms of a set of components that interact with each other and with their context. The behaviour of the system as a whole depends upon the connectedness and interrelationships of its components. Fraser *et al.* (2007) provide a brief review of studies that demonstrate how the social and ecological context in which climatic problems occur is likely to be as important in determining the outcomes, if not more so, than the nature and magnitude of the climatic shock itself. They also draw attention to the methodological challenges of understanding the system dynamics, and demonstrate the use of relatively simple modelling frameworks that capture institutional, socio-economic and ecosystem components. However, systemic research is still the exception in modern science (Gallopín *et al.*, 2001).

The development of theory for systems is comparatively recent. An early approach was von Bertalanffy's (1968) development of 'general systems theory'. Von Bertalanffy, a biologist, was interested in generic patterns of system behaviour seen in wider social issues, and recognized the need to look at the subject as an interactive and adaptive system. His theories have been developed into widely used integrative methods that extend into cybernetics, information systems and complexity science, and that find application in fields as diverse as engineering, business, biomedical sciences and ecological conservation.

The concepts and terminology of both systems and complexity theory have proliferated in interdisciplinary and integrated research, but does systems theory provide the right tools for integrated global change research? Especially in the field of socio-environmental research, there is still a great deal of experimentation and debate about the rigorous application of systems theory. Systems analysis potentially provides frameworks for bridging the 'cultural divide' (e.g. Newell *et al.*, 2005; van der Leeuw *et al.*, 2011), offering scope for richer, more nuanced explanations than any single discipline can provide. It can help counter the over-specialized and over-simplified views that are widely seen as a barrier to the production of useful and usable knowledge in the context of real-world complexity and uncertainty. A strong argument for a systems approach is that it recognizes the importance of the system's context, which cannot be excluded from the scope of investigation. However, determining the boundaries of the system for investigation is far from straightforward, as both the Social Process diagram and the Bretherton diagram show. Arguably, these iconic representations of global change processes reached their limits as research-framing tools because they both incorporated their contexts as components (the human dimensions box in the Bretherton diagram and the environmental processes box in the Social Process diagram).

Despite the proliferation of systems concepts in many academic fields, there is the alarming possibility that global change research could inadvertently be divided by its common systems language (see also Park, 2011). The shared terminology often hides fundamental differences in underpinning theories or world views. Of particular relevance to global change research and Earth system modelling is the social science debate relating to methodological individualism versus 'emergentism'. For the methodological individualist, if the motivations and behaviour of one individual can be observed and explained, then society can be explained as the simple aggregate of individuals. Other thinkers argue that there are facts about the social world that are not reducible to facts about individuals. They argue for the distinct reality and integrity of the social world, which impresses itself on individual behaviour. Are social structures 'real' (and thus capable of being modelled and theorized in their own right)? If society and its dynamics cannot be explained or predicted simply as the aggregate of individual actions, this implies emergent social phenomena arising from complex interactions at the individual level – and complexity of this sort is needed to explain many aspects of social change (e.g. Elder-Vass, 2007). Adding textures to this debate is the fact that modernity has brought many different conceptualizations of 'the individual' – variously as rational, as autonomous, as social and so on (Simon, 1957). To date, a mishmash of divergent assumptions about social and individual dynamics have been embedded in global models, notably in IAMs. To climate modellers, this pragmatic approach may look like it produces useful outputs. To researchers in the other fields whose knowledge is needed for understanding the Earth system, it can result in unverifiable confusion or academic dead-ends.

Nevertheless, significant progress is being made in exploring the dynamics of social systems, in the growing sub-field of social systems theory. Social simulation is a rapidly growing field (Gilbert and Ahrweiler, 2009; Heckbert *et al.*, 2010); there are efforts to capture both the biological imperatives and the cultural dimensions that shape human life (e.g. Ziervogel *et al.*, 2005; Saqalli *et al.*, 2010). Agent-based modelling is a particularly powerful technique in this context. After all, social systems can be defined as those that involve multiple agents with varying intentions and incentives. Using models and observations together – also a core feature of Earth system science – means that concepts of emergence in social systems can be explored more systematically (e.g. Sawyer, 2005; Vogel, 2009; Read, 2010). To date, however, not much of this work has had a well-articulated environmental dimension, and the application of models of social dynamics in Earth system science is still relatively novel. Knowledge that has so far developed disparately now needs to be consolidated.

An ambitious conceptual application of socio-ecological system ideas that explicitly aims to deliver that consolidation was articulated at a Dahlem workshop held in 2005 (Costanza *et al.*, 2007), tracing the long-term historical timeline of human societies, focusing in on the long-term multi-scale dynamics of socio-environmental change. This initiative is developing into a deeply interdisciplinary international research project, linking palaeoclimatologists, archaeologists, climate scientists and historians, anthropologists, economists and ecologists and more. This project, *Integrated History and future of People on Earth* (IHOPE, www.stockholmresilience.org/ihope; see Cornell *et al.* (2010a) and van der Leeuw *et al.*, 2011) aims to recast the narratives of human history in ways that incorporate what we know of the history of the natural environment and its interactions with society.

Another area of significance for global change research is the focus that the social sciences now bring to the modelling process itself – from conceptualization through to application. Given that systems representations are necessarily simplifications of complex realities, for knowledge integration there is no substitute for deliberation and discussions – among the contributors *and* with the users of the knowledge. Rademaker (1982) expressed this as the vital need for '*pondering the imponderables*' once a model has been constructed and run. Fraser (2007) emphasize that rather than driving towards ever more spuriously precise 'prediction' of socio-environmental systems, the modelling process should attempt both to incorporate and to expose the potential feedbacks and different assumptions brought by the scientists and stakeholders. Allison *et al.* (2009) are also explicit that large-scale analyses, like their national-level analysis of economic vulnerability to the impacts of climate change on fisheries, need to be complemented by local, site-specific assessments involving the individuals affected by the changes.

1.3.3 Resilience, adaptation and vulnerability

Since the 1990s, there has been a growing focus on coupled socio-ecological systems and their ***resilience***. The resilience framework was developed by Holling and Gunderson (2001), both biologists (like von Bertalanffy) who extended to the social world their insights from ecological processes. The framework emerged from a deliberate process to develop theories of socio-environmental change. Change is viewed in terms of oscillations between phases of growth and stability, and of crisis and reconfiguration (Figure 1.6). Holling (2001) reviews the key concepts of resilience for linked social, economic and ecological systems. Several properties shape the transformations or future states of a complex adaptive socio-ecological system. Its sparseness or richness sets the system's potential (or 'wealth'), determining the number of alternative options for the future. The connectedness of the elements in the system shapes the extent to which a system can control its destiny. The adaptive capacity of the system determines how vulnerable it is to disturbances that can exceed or break that control.

Resilience research emphasizes some key characteristics of complex systems that inform human dimensions research with an Earth systems perspective:

- *Emergence* has already been mentioned briefly. It implies that the properties of the parts of the system can be understood only within the context of the larger whole – and that the whole cannot be adequately be analyzed only in terms of its parts. Irreducibility is its corollary: true novelty can emerge from the interactions between the elements of the system.
- *Multiple interacting scales*: resilience theory posits that socio-ecological systems are hierarchic, with strong coupling between the different levels. This

makes it impossible to have a unique, correct, all-encompassing (adequate) perspective on a system from any single level; plurality and uncertainty are inherent in systems behaviour. The system must therefore be analyzed or managed at more than one scale simultaneously. The concept of adaptive management (e.g. Peterson *et al.*, 1997; Folke *et al.*, 2002; Olssen *et al.*, 2004; Dearing *et al.*, 2010) is being developed in response to this challenge. The presence of global phenomena that society wants to manage raises questions about the structures and processes of global governance. This has also become a focal area for research and science–policy dialogue (e.g. Biermann, 2001; Biermann and Pattberg, 2008; Hulme, 2010 and the IHDP's project www.earthsystemgovernance.org).

- *Non-linearity*: many relations between the elements of a complex adaptive system do not show linear behaviour. The magnitude of the effects are not proportional – or even in the same direction – as the magnitude of the causes. Counterintuitive behaviour is typical of many complex systems. Accordingly, there is a strong focus in current research on thresholds, discontinuities and 'explosions' or 'collapses' of growth.
- *Multiple legitimate perspectives*: understanding an adaptive system demands a consideration of its context, and, where social systems are concerned, this means a consideration of the many social groupings with an interest in the issue. If these voices are to be considered in decision-making about global change, then this characteristic of socio-ecological systems also has implications for the ways in which global governance can operate.

Other fields of socio-environmental research in the climate context appear to be converging on the language and concepts, if not necessarily the full theoretical underpinnings, of resilience and socio-ecological systems.

Adaptation studies have conventionally been underpinned by economics and policy analysis, generally taking a sectoral perspective on society. Reflecting current lines of academic specialism and policy structures, these analyses have generally considered sectors separately. The Working Group II report of the IPCC's Fourth Assessment Report (2007) demonstrates this emphasis. Its synthesis of adaptation research is divided into chapters for agriculture, transport and infrastructure, coastal zones, and so on. It frames the challenges of responding to climate change largely in terms of the financial costs of adaptation, the limits that these costs impose and the barriers to their implementation. The adaptation plans prepared by the world's poorer countries under their commitments to the national adaptation programme of action[3] of the UN Framework Convention on Climate Change are predominantly focused on sector policy. Swart *et al.* (2009) review Europe's climate adaptation strategies, which are similarly framed in sectoral terms. They recognize that cross-sectoral conflicts present a threat to successful adaptation, with several countries identifying the need to enhance resilience through flexibility in strategic planning.

Adaptive capacity is increasingly defined as synonymous with resilience. Following from the growing acceptance of the idea of a coupled socio-ecological system, the recognition of ecological constraints on social activities and of the role of the natural environment in maintaining social resilience is becoming prominent in policy discourse. It also brings new challenges for policy integration (e.g. Swart *et al.*, 2009; Berrang-Ford *et al.*, 2011). Examples of policy documents that emphasize environmental limits and thresholds include the 2005 UK Sustainable Development strategy (Defra, 2005), the UK Department for Food and Rural Affair's reports on ecosystem services (Defra, 2007), the TEEB report (Kumar, 2010), and the UN Development Programme's Human Development Reports of 2007/2008 and 2010 (UNDP, 2008, 2010).

Vulnerability – of the individual, household, community or nation – has previously been framed very much in terms of situated social research, drawing on the fields of development and international relations. Vulnerability research often uses the language of hazard and risk, rather than of economics and sector policy. Again, the structuring of the IPCC's synthesis reports show this: vulnerability research has generally been reported in regional terms, rather than sectoral, using specific case studies or events as its evidence base. Increasingly, there is recognition that issues experienced in a particular place are likely to have complex interactions across different geographical

[3] National adaptation programmes of action (NAPAs) are the process whereby least developed countries (LDCs) identify priority activities in responding to climate change. http://unfccc.int/national_reports

scales, and that vulnerability can be exacerbated by the simultaneous action of multiple stressors.

Resilience theory has been deployed in bringing vulnerability into a global framework. Turner *et al.* (2003) explain how vulnerability can be regarded as a function of three factors: the exposure to the hazard; the sensitivity of the system, in terms of both human and environmental conditions; and the resilience of the system. This is not necessarily promoting a 'global vulnerability analysis' as such (although Allison *et al.* 2009 show how the framework can be used in a multi-country approach) but it offers new ways to build up a robust picture of human vulnerability to environmental change worldwide, and to devise governance structures to address the problems.

1.3.4 Economics and Earth system science

Economics textbooks describe the discipline simply enough as the study of resource allocation. 'Oikos', the Greek root word, means *home* or *house* or *holdings*, making economics the 'management of the holdings'. Key concepts in economics relate to stocks and capital, material throughput and transformation, value and income – in other words, the holdings themselves, the processes, and the drivers in the economic system.

Most mainstream economic theory has been predicated on the idea of equilibrium: the assumption that, unperturbed, the economic system tends towards a stable state. The transactions of exchange of goods and services in markets are shaped by people's preferences and values, and determine prices, *ceteris paribus* ('all other things being equal'). At equilibrium, the supply of goods and services efficiently meets demand. Where there is inefficiency in allocation, the price mechanism is what shifts demand or supply. Several other idealized assumptions are embedded in mainstream (classical and neoclassical) economic theory. Within resource constraints, utility maximization is the determinant of wellbeing. Decisions about resource allocation are made by a hypothetical unitary rational actor (this is one of the fields underpinned by methodological individualism). Economic demand and supply relationships depend on the assumption of perfect information flows about the goods and services available. Many fields of economics have long traditions of critique of all these assumptions, but it is this idealized body of economic theory that dominates in Earth system science.

Economics shares the language of quantification with environmental science. In that regard it has faced less of a methodological hurdle in integration in global change research than many fields of social science. Integrated assessment models that typically link modules of climate, land use, energy and economics (already mentioned briefly in Section 1.2) are widely used in global climate science and policy, as well as in many regional environmental contexts.

In the global change context, many IAMs embed macroeconomic global trade models (as discussed in Grubb *et al.*, 2002) that apply these concepts of supply and demand. They tend to draw on statistical and empirical analysis of national accounts and of the worldwide flows of raw materials. Typically, they use computable general equilibrium methods to simulate the reallocation of resources through different sectors following an imposed change, such as a policy intervention affecting land use or energy systems. Integrated assessment models have therefore become important tools for the assessment of the implications of such changes, informing decisions about policy and pricing in the emergence of markets for carbon, and potentially also for ecosystem services (the benefits that human society obtains from natural processes and functions of ecosystems). However, as Warren (2011) argues, this area of application of models requires a step change in their treatment of sectors and regions to address the global interconnections. With regard to decision support about ecosystem services, Naidoo *et al.* (2008) and Carpenter *et al.* (2009) emphasize that improvement is needed in the treatment of both the economic and ecological dynamics in models. While full-complexity Earth system models do now represent the linked dynamics of ecosystems and climate well, so far they have not incorporated economic modules. However, progress in this area is being made with some intermediate complexity ESMs and some spatially explicit multi-component IAMs (reviewed in Tol, 2006).

A discussion of the representation of economics in models is outside our scope here.[4] Our aim is to explore how economics concepts are deployed in global change science and policy. It is no surprise that a discipline concerned with the supply and demand of money meshes easily and fundamentally with politics but, mirroring

[4] Books providing an overview of the technical aspects of economic modelling include Nordhaus (1994), which explains the economic theory embedded in the DICE IAM, and Tol et al. (2009) which describes the theoretical and empirical foundations for modelling the economics of land use at the global scale.

the theoretical diversity in the other social sciences already discussed, a wide range of schools of economic thought exist that address the same issues through very different lenses.

A marker of the emergence of the field of environmental economics was the publication of *Blueprint for a Green Economy* (Pearce *et al.*, 1989). Perhaps the single most influential idea of this popular book was its focus on environmental externalities – costs or benefits to society that are not captured within markets. Pearce and his colleagues pointed out that a consequence of the fact that nobody owns the natural environment can be that it is valued at zero in decision-making processes, even though both environmental costs and benefits can be very significant indeed. The book described a strand of research into ways of quantifying environmental values in monetary terms and incorporating these environmental costs and benefits into decision-making processes, which already often operated on the basis of cost/benefit analysis.

In recent decades, methods have been developed for assessing the value of environmental goods and services when market prices do not exist (e.g. Pearce and Turner, 1990; Defra, 2007). These valuation and value-transfer approaches were initially applied to decisions in local contexts such as waste management and conservation-site selection, and are now accepted inputs to more complex and regional concerns like river-catchment planning and integrated coastal zone management. The thinking outlined in *Blueprint for a Green Economy* has informed a wide range of policy measures, such as the UK's landfill disposal charge, urban congestion charges and carbon emissions trading. Its neoclassical perspective has had a lasting influence, traceable in the emphasis on environmental assets, the definition and allocation of property rights, the development of markets for environmental goods and services, and a leaning towards economic incentives rather than, say, taxes or regulatory control as preferred policy instruments. The UK Government-commissioned Stern Review (Stern, 2007) that quantified the costs of responding to climate change was a product of this tradition. Thus, its key recommendations were strongly oriented towards market mechanisms: in identifying a collective global way forward, '*policy must promote sound market signals, overcome market failures*' (Stern, 2007, executive summary).

Another strand that has developed in recent decades is 'ecological economics', a radical project to rewrite (macro) economics integrating natural-resource constraints. Early proponents were Daly (1974, 2009), a World Bank economist, and the ecologist Ehrlich (1989). Ecological economists base their arguments on the idea that the economy and social activity need to be seen as sub-systems of a global ecosystem. They call for an explicit recognition of ecological 'limits', and the maintenance of critical natural capital (reviewed in Ekins *et al.*, 2003). A landmark paper for this field was the assessment by Costanza *et al.* (1997) of the global total annual value of the services that nature provides to society, such as storm-surge attenuation by marshlands, nutrient cycling, the regulation of atmospheric composition and so on. Until this analysis of the 'value of nature', the magnitude of the opportunity costs of human development had never been totted up. Damage to the environment was largely incremental and – as Pearce and his colleagues had argued – it was rather invisible to the policy process, even if it was starkly evident in other ways. In this paper, this fact was pointed out in ways commensurate with other decision-making processes. In practice, of course, the notional 'total world value' of nature has little immediate relevance to policy-making. In most day-to-day practice about environmental-resource use, decision-making is done on a local level, and global-aggregate analysis misses the mark. In a rigorous environmental economic analysis prepared in response to shortcomings in the Costanza *et al.* article, Balmford *et al.* (2002) calculate a benefit:cost ratio of 100:1 for the global conservation of ecosystems. Despite the conclusive magnitude of the net economic benefit in the Balmford *et al.* analysis, development and conservation priorities have not been transformed on that basis, which suggests that decision-makers do not use esoteric global assessment numbers like these.

What caught policy-makers' attention in this debate was the articulation of the concept of ecosystem services in economic terms, which could form the basis for the creation of real markets in previously 'invisible' natural resources, and thus provide a different set of institutional levers to promote and incentivize resource conservation. Daily *et al.* (2000) described early developments in the creation of markets for ecosystem services, envisaging the trading of '*new environmental products, such as credits for clean water…*' on the stock exchange. The Millennium Ecosystem Assessment (MA, 2005) brought ideas from ecological economics into mainstream policy by emphasizing the dependence of human society on well-functioning ecosystems. The MA framed environmental processes and functions as providers of benefits to human society – the ecosystem services (Ehrlich and Mooney 1983) that nature confers. It also framed a well-functioning nature as a scarce resource, documenting the relentless worldwide process of human-induced environmental degradation and loss of biodiversity. It stopped short of quantifying these trends in economic terms, but the policy world had taken notice. The language of ecosystem services now pervades climate, environmental and conservation policy (although few actual markets have been created so far). In 2007, the environment ministers of the G8 countries and five emerging economies launched the Potsdam Initiative for biodiversity. Among its commitments are a promise to '*initiate the process of analysing the global economic benefit of biological diversity, the costs of the loss of biodiversity and the failure to take protective measures versus the costs of effective conservation*', and a commitment to devise and support financial mechanisms for markets to trade ecosystem services. The report entitled *The Economics of Ecosystems and Biodiversity* (known as the 'TEEB report'; ten Brink *et al.*, 2009; Kumar, 2010) documents this promised analysis.

Balmford *et al.* (2011) and Fisher and Turner (2008) tease out some of the tangles that remain in the concept of ecosystem services as outlined in the Millennium Ecosystem Assessment. The MA classification (provisioning, regulating, supporting and cultural services) has drawn policy-makers' attention to the interdependencies of the many ecosystem processes and functions, but it has been conceptually problematic for ecologists and economists alike. It would be helpful – for scientists *and* policy-makers – if we made a clear distinction between ecosystem processes (what nature does), services (what nature does that we can use or depend upon) and benefits (what we actually do use and value). Any credible Earth system science response to the often-articulated demands to 'model global ecosystem services' (e.g. Perrings *et al.*, 2010) depends on understanding and accommodating this distinction.

A parallel set of critiques is focused less on the conceptual principles and methods being used in ecosystem services economics than on the policy implications and applications. Cornell (2010b) argues that the ascendance of global market mechanisms in this context is backtracking on well-established international sustainability commitments. Cornell (2011) explores the perspectives and arguments made in other critical analyses (Spash and Vatn, 2006; Norgaard, 2010) of the ecosystem services concept. In short, although the concept of ecosystem services has proved to be a powerful and useful framework highlighting the risks of human-caused environmental degradation, responses that seek to apply its economic dimensions need to recognize the complexity of the socio-ecological system, and to accommodate the issues of equity and justice that are equally essential components in the sustainable management of the global environment.

The ecosystem services concept highlights how shifts in public-policy discourse reflect and influence the value placed on the natural environment. For instance, a socio-technical agenda dominated in the 1950s, with environmental degradation a consequence of the pursuit of 'a decent standard of life'. In the later twentieth century, neoliberal public policy was strongly oriented towards contributing to economic growth, which has driven today's reliance on market mechanisms to incentivize care for the environment on a global scale. At the start of the twenty-first century, there has been an international shift towards 'redefining wellbeing', in terms of quality of life not quantity of material consumption (e.g. Stiglitz *et al.*, 2009; Dolan *et al.*, 2011). Sometimes called the happiness agenda, it implies a quest for very different indicators of societal wellbeing 'beyond GDP'.

The first issue we want to highlight in this regard is the flurry of methodological developments this has brought. Economic tools and approaches that were previously marginal interests have become prominent in this current context. These include multi-criteria analysis that includes environmental values, rather than conventional cost/benefit analysis; and participatory processes in economics, both for the deliberative optimization of economic valuations, and for a more consensual discussion of implementation of policy options. Echoing the debates in the social sciences about emergence is the idea that communities may have shared values. Incorporating these into valuation studies can only be determined through dialogue, rather than assuming fixed individual preferences (Turner, 2010). From a sustainability perspective, this focus on democratic engagement and transparency in economic valuation is a good thing. However, it shifts away from predictive global socio-environmental modelling as it has been envisaged to date.

A second point is that economic growth is increasingly becoming 'de-materialized' (Panayotou, 2003; Ausubel and Waggoner, 2008), with economies relying less on the production and consumption of 'stuff' (actual physical goods) for the generation of wealth and wellbeing. The long-run prospects for economic growth (and all the benefits it brings to society) require a stronger separation of economic goods from 'bads', such as decoupling economic growth from environmental impact, wellbeing from material consumption, and of course energy provision from fossil-fuel combustion.

The idea of a 'Green New Deal' (e.g. Barbier, 2010) or a greening of the economy (with green infrastructure built by green collar workers, in the words of political scientist Timothy Luke) has gained traction in the light of both a suppressed global economy and the growing recognition of the need to mitigate climate change. The idea does not always mean a reversion to much more local, low-impact, low-tech modes of living. The United Nations Environment Programme (UNEP, 2011) calls for '*investing two per cent of global GDP in greening ten central sectors of the economy in order to shift development and unleash public and private capital flows onto a low-carbon, resource-efficient path*'. The UK Conservatives Gummer and Goldsmith (2007) note that '*The pricing of carbon itself represents a host of exciting opportunities for reinvigorating the economic system and companies within it – for flushing out old power structures, opening space for new entrants and technologies, stimulating job creation and encouraging nimbler, lighter management.*'

Earth system science already plays a uniquely powerful role in this latter vision, whether the scientists know it or not. One fundamental way is in the pricing of carbon (other emerging ways include informing the design and monitoring of climate mitigation through biosphere management, as discussed in Chapter 7). Dietz (2007) highlights one specific issue in this regard: the social cost of carbon, which is the 'shadow price' used by policy-makers in pricing carbon, depends not on current levels but on the future trajectory of CO_2 concentrations in the atmosphere. Policy choices can determine the level of emissions, but the Earth system links between emissions and concentration are not a matter for policy guesswork. Optimal policies depend fundamentally on the scientific knowledge that only Earth system science can provide.

Although Earth system models are still a considerable way off being able to represent the interplay of climate, ecology and economics in the necessary detail, there are foreshadows of the part envisaged for projections and predictions of ecosystem services in the future 'green' economy. McAfee (1999) wrote with concern that '*by the logic of this paradigm, nature is constructed as a world currency and ecosystems are recoded as warehouses of genetic resources for biotechnology industries.*' Perrings (2010) confirms that this is now precisely the case, although he also highlights progress in the design of governance systems that treat biodiversity as a transboundary public good.

In recent years, as climate adaptation and mitigation have become major policy issues, there has been a growing emphasis on the natural environment in development economics. Development economists have long been concerned with social questions of equity and legitimacy in resource allocation (e.g. Boyd and Juhola, 2009), along with the conventional economic attention to efficiency and effectiveness. Research and application in this field have been influenced more than mainstream economics by a rights-based ethics, rather than purely a utility function. Sen (1973) pointed out that utilitarianism does not deserve its 'egalitarian reputation' and called for economics to concern itself more with fairer treatments of inequality and welfare distribution. However, a common critique of the globalization of the economy is that social dimensions have been sidelined in favour of economic prerogatives. In 2001, Meier and Stiglitz collated a very diverse set of sociological and economic perspectives on economics and development, exploring this tension. Some of these analyses (Thomas 2001; Yusuf and Stiglitz, 2001) also explicitly considered the natural environmental and climate change.

Many of the polarities discussed in Meier and Stiglitz's book are still evident in today's debates about environmental justice. The UNEP Green Economy report (2011) notes the persistence of inequity in the distribution of environmental costs and benefits, and emphasizes again, as Sen did 40 years ago, that equity needs to be made a parallel priority in development. Failings in integrating the social, environmental and economic dimensions can be seen in concern about the 'double jeopardy' problem where the world's poorest people are likely to be most exposed to climate hazards but also are likely to have the least adaptive capacity (O'Brien and Leichenko, 2000; LaFleur *et al.*, 2008); in the equity debates relating to the 'contraction and convergence' approach (GCI, 2005) used in the UN Framework Convention on Climate Change, which has focused attention on the emissions associated with the historic development of the world's rich countries; and of course in the discourses of payments for ecosystem services and the Kyoto and post-Kyoto mechanisms for climate mitigation (Griffiths and Martone, 2009; Ikeme, 2009; Leach, 2009; UNEP, 2011).

To close this section, we highlight a couple of contexts where social research, economics and environmental science are meeting, allowing for deeply transdisciplinary approaches to global change.

A stronger focus on human behaviour is evident in many areas of environmental change, society's responses, and environmental risk management. This can be seen in the research and policy discourse, and the expansion of environmental themes in areas such as behavioural economics and social psychology. An iconic character in this field is the Nobel Laureate economist Kahneman whose research highlighted the often-irrational decision-making of human beings, and the importance of subjective wellbeing (in other words, people can feel happ. when all indicators suggest they should not be, and vice versa). Evidence is growing that climate impacts are strongly mediated by these behavioural and social dimensions. For instance, Fraser (2007) documents cases where big drought events (in terms of absolute water shortage) did not cause commensurately big effects on agriculture, as well as cases when small droughts had huge impacts, in part because of the nature of people's responses. Findings like this indicate that, in responding to climate change, people's behaviours need to change. These behavioural aspects have profound implications for the design of policy incentives for socio-economic or technological change, and for concerted societal action (Shibutani, 1961; Crosweller and Wilmhurst., in press; Cornell and Jackson, in press). This body of evidence also presents challenges to the analysis and modelling of systems; issues of human choice and agency have always been problematic in modelling, but the 'systems behaviour of human behaviour' is plagued with non-linearities and surprises.

Despite all the challenges outlined in this chapter, the research communities variously known as 'Impacts, Adaptation, Vulnerability' or 'Vulnerability, Adaptation, Resilience' are showing an entrainment of social and economic insights into Earth system science. In Chapter 5, we discuss the ways that the future scenarios being developed for the IPCC's fifth and subsequent assessment reports aim to incorporate social and economic narratives better than before. But this trend extends beyond the subset of scientists involved in the IPCC. Several major international conferences have explicitly sought to bring these academic, policy and practice communities together for more effective dialogues. These include Earth System Science 2010, Resilience 2008 and 2011, and Planet Under Pressure 2012 (Table 1.2). International strategic research planning processes have also mapped out ways to improve the transdisciplinary interaction that is needed to inform responses to global change. These include the 2010–2011 ICSU/ISSC 'Visioning Exercise' for Earth system science, and the European Science Foundation's RESCUE Forward Look on science needs in the Anthropocene. These efforts are taking integrated Earth system science to a new level.

1.3.5 Societal responses to environmental change: the policy context for Earth system science

The changing roles of the natural and physical sciences and social and human sciences in global change research mirrors a growing policy focus on the 'human dimensions' of global environmental change. It reflects a shift from needing first to characterize the problem adequately to needing now to inform responses and solutions (Box 1.4). The recognition of the interlinked socio-ecological system increasingly pervades what previously were either environmental or social policy contexts.

For example, the notion of a coupled socio-ecological system is becoming more widely applied in the policy context. In the UK, the national sustainable development strategy, *Securing the Future* (Defra, 2005), articulates its five guiding principles within a socio-ecological framework. In its top-level principles, it makes a clear statement that society should aim to optimize its wellbeing while operating within environmental limits. This balance of nature and society is mediated and managed through good governance, good application of (scientific) knowledge, and good economics. A shift in the focus of the UNDP Human Development Reports can also be seen, from addressing poverty in narrowly socio-economic terms to a deeper consideration of its causes and consequences in terms of environmental justice (UNDP, 2008). There has also been a clear trend from the first IPCC assessment report in 1995 to the latest in 2007 towards greater integration across the socio-environmental divide. Early assessments were criticized for very piecemeal treatment of social concerns in contrast with a richly elaborated and resource-intensive theoretical treatment of the physical climate science. The current round of assessment includes a complete reconfiguration of the future scenarios used

Table 1.2 Some dialogue initiatives for integrative Earth system science
All these initiatives aim to provide a forum for people working with the complex dynamics of interconnected social–ecological systems to discuss the challenges of future societal development. They seek to highlight new directions for understanding the interactions between humans and our environment, and strengthen the much-needed interactions between the natural and social sciences, and between policy, assessment and research.

Initiative	Further information
Resilience 2008: *Resilience, Adaptation and Transformation in Turbulent Times* Stockholm, April 2008 International conference convened by the Resilience Alliance, with the Swedish Academy of Sciences and ICSU.	http://resilience2008.org WebTV coverage of discussions and key presentations are available on http://resilience.qbrick.com/
Resilience 2011: *Resilience, Innovation and Sustainability: Navigating the Complexities of Global Change* Tempe, AZ, March 2011 International conference convened by the Resilience Alliance, with Arizona State University.	www.resilience2011.org
Earth System Science 2010: *Global Change, Climate and People* Edinburgh, May 2010 The first IGBP AIMES Open Science Conference, with QUEST, the UK NERC research programme for Earth system science.	http://quest.bris.ac.uk/workshops/AIMES-OSC Conference proceedings were published in *Procedia Environmental Sciences* (2011), vol. 6 www.sciencedirect.com/science/journal/18780296
Planet under Pressure 2012: *New Knowledge Towards Solutions* London, March 2012 International conference convened by the four international global change programmes IGBP, IHDP, WCRP and Diversitas, and the ESSP.	www.planetunderpressure2012.net
Earth System Visioning: *Developing a New Vision and Strategic Framework for Earth System Research* International consultation and strategy development exercise by ICSU and the ISSC.	www.icsu-visioning.org Grand Challenges identified for Earth system science for global sustainability (Reid *et al.*, 2010).
ESF Forward Look: *Responses to Environmental and Societal Challenges for our Unstable Earth (RESCUE)* International consultation and horizon-scanning exercise by the European Science Foundation.	www.esf.org/rescue Articles based on the working group discussions are being published as a special issue of *Environmental Science and Policy.*

for the climate modelling, precisely so that a richer set of socio-economic storylines can be developed in line with the global projections of climate.

The immediate question that this shift from pure science to a solutions-oriented application should prompt for Earth system scientists is: what is policy? Who makes and implements it, and how, when and where? We can state in the broadest terms that policy is a societal decision about how to steer itself (as in Pielke, 2004), but we still need to recognize that policy is fluid and evolving.

Coordinated climate policy first developed in the 1980s. At the first World Climate Conference (Hare and White, 1979), participants were mostly invited scientists, discussing the physical science of climate change and natural hazards, and the social impacts of change. After that event, where scientific consensus coalesced about the threats of climate change, major scientific and environmental bodies including the WMO, UNEP and ICSU coordinated efforts rapidly to mobilize a societal response. The landmark Villach meeting in 1985 (Franz, 1997) set the foundations for the IPCC, which was established in 1988. The IPCC remains a vitally important feature now in the climate policy landscape, as the intergovernmental forum for scientific synthesis. The prime instrument of climate policy is the United Nations Framework Convention on Climate Change (UNFCCC; adopted in 1992; http://unfccc.int) with its regulatory targets and mitigation instruments, translated into regional and national policy responses (described in Schneider *et al.*, 2010). In the currently ongoing synthesis activities of IPCC's Working Group II (Impacts, Adaptation and Vulnerability), there is a stronger steer towards more directly addressing the specific policy-oriented information needs of the UNFCCC.

A major theme in this chapter and throughout this book is that global change involves much more than just the climate system. The evolution of international policy for many aspects of environmental change and development have paralleled climate policy. Third World development concerns prompted the creation of the UNDP in 1971. The 1972 Stockholm Conference on the Human Environment (ECO I) led to the creation of United Nations Environment Programme, devised to be the 'environmental conscience' of the UN system. The implications of land-use change and deforestation in dryland regions led to the UN Convention to Combat Desertification in 1977. The Brundtland report (1987) and the 1992 United Nations Conference on Environment and Development (the first Rio Earth Summit) marked the formalization of global policy for sustainability.

Attention is needed to the challenges of integration of all these policy strands at two levels. The first is the integration of environmental change into existing (national, sectoral) policies. The second is the integration of the many 'jigsaw-puzzle pieces' of policies targeted at different aspects of environmental change (Nilsson and Eckerberg, 2007), which could potentially have conflicting goals or instruments. Scientists aiming to engage effectively with policy need to understand this complex policy landscape. One example of a concerted effort to bridge science and its complex policy context was the 2009 International Nitrogen Initiative's expert meeting of the Convention on Long-range Transboundary Air Pollution and the Convention on Biological Diversity, which explored the scientific links that need to be addressed in developing the evidence base for these two conventions, and also made a preliminary consideration of the links to climate science for the UNFCCC (UNECE, 2009). This event showed how considerable benefits for scientific work supporting policy discussions can be reaped from increased collaboration among the various scientific communities currently tackling environmental problems as if they were separate issues.

Compared with the institutions and instruments of national-level policy, global policy faces particular challenges. For any environmental management effort to be effective, the spatial reach of governance systems must match the spatial scale of the problems they seek to address. Earth system science gives insight into the workings of global-scale problems but, in the absence of a planetary authority to steer a desirable and sustainable pathway (as suggested by Schellnhuber and Kropp. 1998), the notion of 'Earth system governance' demands attention to effective political solutions. The strategic overview that global governance institutions and instruments may implement also needs to meet local needs (Berkes, 2002), which presents dilemmas and operational obstacles. Commitments to forms of democratic participatory involvement in decision-making (for persuasion, consensus, and legitimacy) are enshrined in many global agreements and national constitutions, but are not mirrored in structures for such engagement at the global level. Adaptable governance is needed, capable of provisional and responsive decision-making in the context of uncertainty about future climate and its impacts. And a critically important question still remains open: who pays for the processes of global governance and society's responses to climate and global environmental change?

These are very real concerns and tensions in current debates, particularly in climate mitigation which is necessarily a global issue. Chapter 7 returns to some of the global policy and governance issues that shape the context of mitigation, and Chapter 8 reflects on the knowledge gaps that science can help fill. In Box 1.5, we indicate some recent books that exemplify how the social sciences and humanities are addressing global change. In our closing section, we focus on what lessons can be drawn from the transdisciplinary efforts to date that can inform twenty-first century Earth system science.

Box 1.5 Other information resources

Several recent social science and humanities books address 'the climate dimension' of human systems. Here are some that bridge the diverse fields of scholarship:

- *The Politics of Climate Change* (2009), by sociologist Anthony Giddens, starts from the premise that although the science and policy of climate change have a very high profile, the actual politics of climate change is still rudimentary. Giddens argues that the political changes needed for responses to climate change should be mapped out in the context of the political structures and institutions that currently exist. The nub of the challenge is that people will only mobilize politically for action in the face of climate change when its effects become tangible problems in their experience – by which time it is very likely to be too late to fix the problem. In Giddens' view, then, a key part of the solution lies with getting people to recognize climate risks as real and pressing.

- *The Economics of Climate Change* (2007), widely known as *'the Stern Review'* after Sir Nicholas Stern, the Treasury economist who led this major review for the UK Government, considers the economic impacts of climate change, and also of climate mitigation. Its starting point was that a clear exposition of the available economic analyses and current understanding of the global impacts was made and shared widely, then, rather than each nation trying to devise their own policy positions in isolation, achieving international agreements on action would be more straightforward. It departed from many previous economic studies by taking an explicitly risk-averse position in its modelling studies, changing the balance between present and future values, and addressing the disproportionate impacts on poor regions.
- *Interdisciplinarity and Climate Change: Transforming Knowledge and Practice for our Global Future* (Routledge, 2010), edited by philosopher Roy Bhaskar and colleagues, brings insights from the critical realist school of philosophy to the challenges of interdisciplinary and action-oriented research in many contemporary socio-environmental issues (including energy, food, consumerism and other global issues), and the problem of linking theoretical knowledge to practical action in today's society.
- Historian Clive Ponting's 2007 *New Green History of the World: The Environment and the Collapse of Great Civilizations* is a revised edition of his book published in 1991. He was one of the first scholars to take a long look back, and to consider what this meant in terms of society's prospects for the future. While he does not explicitly consider a systems perspective, he does give a careful historical exposition of the interplay of human and environmental change.

1.4 Creating usable and useful integrated research about the Earth system

In the olden days, or so goes the story (Balconi *et al.*, 2008), government shaped society, and science informed government. Now both governance and the role of science in society are seen in very different terms. States have lower importance in steering society, while international agencies and corporate actors have higher (Paavola, 2007; Biermann and Pattberg, 2008; Jordan, 2008; Moser, 2008; Paavola *et al.*, 2009). Interactions between individuals have been radically enabled through information technologies and the new media, changing patterns of power, participation, activism and learning. And alongside these changes, science has changed too. The enormous technological investment and increasing specialization in research has put some areas of scientific knowledge out of reach of non-scientists and, as von Bertalanffy noted even back in the 1960s (von Bertalanffy, 1968), it has also tended to leave scientists encapsulated in their disciplinary areas. Countering that is a significant trend in the 'democratization of science' (e.g. Funtowicz and Ravetz, 1993; Carolan, 2006), bringing a stronger focus on issues such as communication, public understanding, policy engagement as part of the scientific research process, and the handling of uncertainty and contested knowledge.

Insights from Earth system science are being channelled into a context of complex social behaviour and political positioning. The end goal of working at the science–policy interface is that society can use these insights to respond with more confidence to the current and projected environmental changes. But although the goal is clear, a great deal needs to be done to ensure that the research being done is both useful and usable.

In this chapter, we have mapped out some of the issues and recent positive developments in the expansive, varied and changing terrain of Earth system science for the Anthropocene. Here, we revisit some of the key themes, paying attention to what they mean for the application of this science.

To begin with, we emphasized the conceptual shifts that researchers in all the contributing fields have needed to make in turning their attention to the human component of the Earth system: human society is an intrinsic part of the Earth system while it is also the collective mind observing, researching and intervening in its dynamics. The balance of experimentation, observation, abstraction, theoretical coherence, and subjectivity or objectivity all determines what constitutes scientific evidence. Global environmental change has been a nexus for change in this balance, reframing our role as scientists within the system that we study.

If the science really is to influence social directions, then partial, over-simplified, or misapprehended knowledge presents tangible, potentially enormously costly risks. A precautionary approach pushes us towards more transdisciplinary integrated knowledge; useful science in today's environment *must* draw on all the available expertise and insight. The scholarly requirements for new integrative working need attention in parallel. We still have some academics (Tol, 2006) arguing that '*Like car repair is best left to mechanics, modelling is best left to modellers*', but as Rademaker pointed out many years ago (1980), '*Modeling is the easiest part of the job. Detecting the right questions and delivering the desired answers in the right language at the right moment is far more difficult.*'

However, we risk putting a too-utilitarian perspective on the matter. We seek understanding of our environment because it is enthralling. We want understanding of how our environment works at the global scale – but not just at that level. After all, the large-scale workings of the planets in our Solar System have long been known. The fascination lies in seeking knowledge beyond the regularities, seeing how small changes can have big and unanticipated consequences, seeing patterns in the complexity, and testing and probing our knowledge in new ways.

A systems perspective provides a common ground for this exploration. Not all scholars who 'think in systems ways' articulate it in those terms, just as not all of the theoretical literature currently produced about systems is of use to our Earth system inquiries. Nevertheless, many of the contributing fields of study now engaging in global change research have well-established foundations in systems thinking, and so also do many of the end-users of the science. Policy integration, after all, is an archetypal process of dynamic accommodation of complexity, contingency and causality.

Having the same ground underfoot is important, but traversing the shifting terrains of global change still demands attention, thought and dialogue. Like any frontier exploration, global-scale transdisciplinary research is uncomfortable at times. Absolute objectivity – in the sense of the traditional scientific ideal of single-variable experimentation under controlled conditions – is not possible in Earth system research, so other ways are needed of ensuring adequate scientific scrutiny and verification of claims. There will necessarily be debates, sometimes conflicts. Better forums are still needed for the transdisciplinary interaction and public and policy engagement that must underpin the envisioned developments in Earth system science. In terms of the science itself, this entails moving beyond pragmatic but over-blunt numeric approximations of socio-environmental processes to agreeing the rules for integration of skills and knowledge among contributing fields of study (as argued by Liverman and Roman-Cuesta, 2008). For useful outcomes, Earth system scientists also need to pay closer attention to the practices and ethics of engagement with policy and wider society (Demeritt, 2001; Hulme, 2008). In short, institutional frameworks need to continue to evolve for research itself *and* for society's responses to global socio-environmental change, better supporting these interfaces and actively encouraging the dialogues and practices that are needed.

For our science to be useful, we need much better ways of addressing the mismatch in scale of global processes and local agency (discussed well by Wilbank and Kates, 1999). Global-scale policy concerns come under the spotlight with the rising attention being given to climate mitigation interventions ranging from biofuel mega-plantations through to geoengineering. Society may decide that it has no option other than to attempt to control climate deliberately though large-scale planetary interventions, but Earth system science should have something to say about *how* this might need to be considered. If we understand climate change essentially as a glitch in the planet's radiative balance, then it is not unreasonable to seek to tweak the planet back, by modifying the physical aspects such as the greenhouse gases in atmosphere, or the reflection or absorbance of Earth, or even by optimizing the biosphere. But as scientists, we may want to issue a caution: we should be aware that a system as intricate and interlinked as Earth may not respond like clockwork.

The multiplicity of theories of biophysical change, human behaviour and the social environment are being connected to the contexts of policy and practice through the lens of global environmental change. The remainder of this book gives an overview of the science of global change as we currently understand it. We close, in optimism, with E. O. Wilson's line (1998; p. 12):

> … If we dream, press to discover, explain and dream again, thereby plunging repeatedly into new terrain, the world will somehow become clearer and we will grasp the true strangeness of the universe. And the strangeness will all prove to be connected and make sense.

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