Chapter 5

Exploring futures with quantitative models

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When a group of scientists discusses models, they can expect some shared understanding of what this term means. When the general public hears the word models, it conjures up a range of images, from fashion icons to miniature trains, but rarely the kind of internally consistent formalised reasoning meant by scientists. In this chapter we show that models and modelling are more familiar and less arcane than people think. All humans use models, consciously or unconsciously, because models are the guidebooks that help us navigate the world we live in. However, as the modern world has become more interconnected and complex, the intuitive models that have served us for millennia are increasingly guidebooks to the past, and of declining value. Here we argue that in a modern world that is so much a product of advances in science, the most reliable guides are models based on scientific principles. We also emphasise the importance of broad participation in the modelling process and discuss ways of achieving this at national scale.

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1 Introduction

The collision of science and intuition

Fundamentally, all models are simplified versions of reality. We use them as learning tools when reality itself is too difficult to handle [Boschetti et al., Chapter 8 in Volume 2; Perez, Chapter 10 in Volume 2]. To be useful, they must reproduce the aspects of the world we are interested in with sufficient accuracy to let us ignore many complicating factors without being led catastrophically astray. Scientific models are distinguished from other models in that they must conform to scientific understanding of real-world processes and the laws of nature (e.g. conservation of mass and energy), and as such are internally consistent. This constraint does not exist for the intuitively formed models used to guide day-to-day behaviour and participation in society, which derive from 'world views'. World views are a form of intuitive (subconscious) model, described by Cocks [Volume 2, Chapter 13] as, '…a coherent system of fundamental beliefs that describe some reality of interest… a thinking tool, a cognitive technology, which provides a first-stop mental model when seeking understanding (What's happening?) or when making decisions (What-to-do?)'. Defined in this way, world views are synonymous with 'narratives', which Raupach [Volume 2, Chapter 14] describes as strongly, even viscerally, held beliefs about the way the world works or ought to work.

People get their world views (or narratives) from many sources—parents, peers (e.g. friends, sporting teams, ethnic groups), education, experience and religion. Peer group pressure is a major determinant of behaviour [1] and in the modern age self-reinforcement of personal views and prejudices through the internet is increasingly important [2]. We tend to sympathise with those who have similar world views to our own [3, 4]. This is because, while world views help us understand our world and anticipate change, they are mostly used as filters that guide our interpretation of other models—either scientific models or the world views of others. Conflict between non-scientific world views, often those that are held unconsciously, and the deductions of scientific models can be a major source of misunderstanding or even conflict.

Intuitive models based on secular ideologies and religion, which might have served humans well when they were dealing with conditions on relatively small scales (e.g. day-to-day activities of hunter-gatherer societies [5]), often failed past civilisations that outgrew their resources [6] and are proving to be ill-suited to dealing with the sheer scale of modern activities. It is no longer sufficient to use commonsense models based on collective past experience, because no previous generation has faced the limits of the natural world at a global scale. Technological development has allowed humanity to shape the modern world to such an extent that we now appear to have entered a new geological epoch, the Anthropocene [7]. Moreover, technology has changed the way people interact, while simultaneously allowing them to satisfy their aspirations in ways that were undreamed of when the decision-makers of today were growing up and setting their mental baselines. Science has a transformative explanatory role in dealing with potential future change because, unlike other means of comprehending the world, it is continuously subjected to testing against reality. Scientific hypotheses must in principle be falsifiable through comparison with observations [8] and, as new information becomes available, be refined or even overthrown and replaced [9]. This scientific method is the foundation of the modern world. We argue that models conforming to the scientific method are a critical component of any effective means of shaping policy meant to address challenges associated with our collective future.

In the following sections we will explain in more detail what we mean by scientific and quantitative models, what they are for, what is in them, how we use them, and give examples of models in action. First though, it is instructive to expand on the kind of conflict that we as scientific modellers often encounter when our assumptions and predictions conflict with deeply held world views. We can do this through a simple example. Let us start with perhaps the simplest model of our world, as a planet where people are a part of the system. A visual representation of that idea is the sphere of the natural world with all our social and economic engagement played out upon it (Figure 1). To most scientists, this simple picture would seem unexceptionable. However, large slices of humanity may find it uncomfortable or confronting. Psychologists have found that humans fall roughly into two ways of thinking about the world—those who think it is just and those who do not [10]. Moreover, some major religions and early Western thought explicitly place man outside the natural order [11]. This has meant that when other models (e.g. scientific ones) have proposed a connection between the two and that resources are limited, this has led to confusion or dismissal ('Why do that? We didn't have to worry about it in the past…' or 'That can't be right, it is here for us, the world wouldn't play tricks on us like that, that's not fair…') or even to bitter or deadly disagreement [12]. Such confrontations did not happen when human populations were small, because the bounds of the natural world seemed distant and beyond the horizon of any impacts people might have had upon it. Societies saw no need to anticipate what those impacts might be. Today is different. Population has expanded to the point where we have a global civilisation and the natural boundaries of our planet are tangible.

In the past it was not uncommon for civilisations to expand to a point where they encountered local boundaries [6, 13]. However, even then, humans rarely extrapolated their intuitive guides—their local models of their interaction with the world—to the point where available technologies and cultural behaviours had

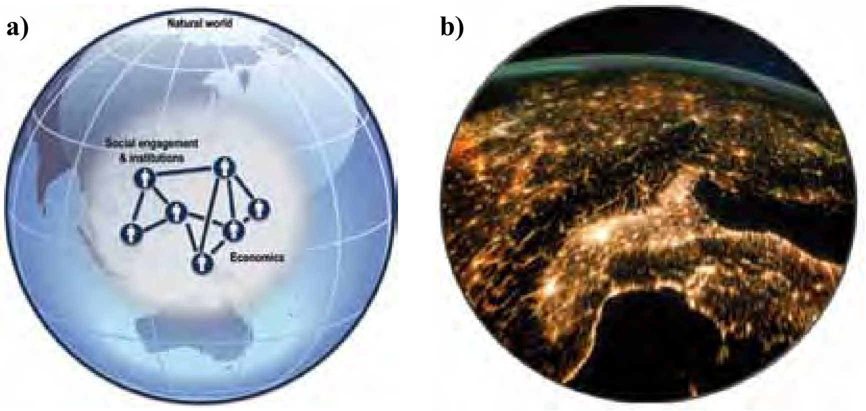

Figure 1: Conceptual model of how the social and economic systems play out within the bounds defined by the natural world that supports them: **a)** as a schematic diagram, and **b)** as demonstrated by a photo[1] of central and eastern Europe at night taken from the International Space Station in February 2011. It shows the thin band of the atmosphere arcing across the top of the image and light spilling from cities (highlighting the hot spots of human economic and social activity and contrasting strongly with the dark waters of the Mediterranean and Adriatic).

impacts on the limits of living space, food supplies or social structure. Lacking this anticipation and warning, civilizations collapsed when they passed boundaries (natural or social) and could no longer support themselves [14]. Taking the fate of those past cultures as a warning, modern society is realising that it is important to think about what happens when the demands of global civilisation reach social and ecological boundaries. However, there are many different versions of how people think this collision will unfold, especially through the next few decades.

In the developed world two versions of the future dominate—the 'sustenance' and 'expansion' narratives [Raupach, Chapter 14 in Volume 2]. The sustenance narrative assumes that our global social and economic system will collide with the bounds of the natural world and that a devastating shock will result (Figure 2a). In contrast, the expansion narrative assumes that something—for example, technological advances—will act as a buffer, preventing this collision (Figure 2b). The many acrimonious arguments about climate change, population growth and economic development that are occupying society at present are rooted in the fact that people do not share the same world view and so are coming to different conclusions about how the world will respond to this collision. This tension can also be exploited by vested interests that spread misinformation exacerbating any differences [15]. A direct result of this has been a persistent and potentially growing gulf between what science predicts human actions will mean

[1] The original rectangular photo from NASA has been remapped on to a circle here for comparative purposes, but has not been modified in any other way.

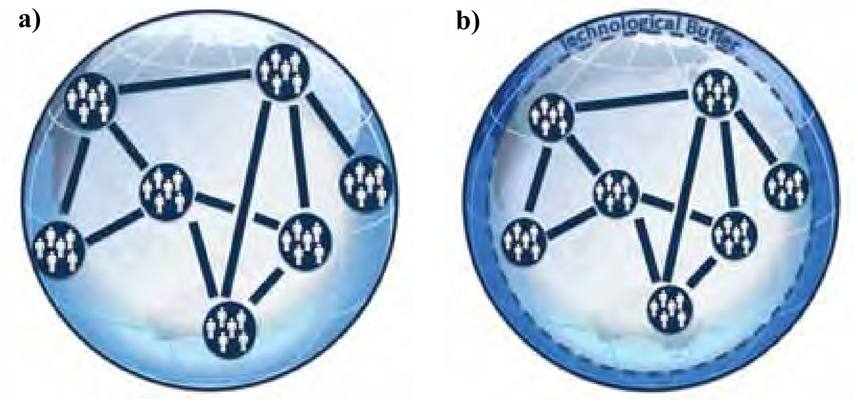

Figure 2: Simple alternative models of the future response to changing population size: **a)** the social and economic system reaches the bounds of the natural world, and **b)** some buffer (e.g. technological innovation) prevents the social and economic system from colliding with the bounds of the natural world.

for our future climate and wellbeing and the appreciation of the general public (or at least some parts of it) of these scientific realities.

Anthropogenic climate change provides an example of the clash of narratives at global scale, but equivalent conflicts are playing out daily at smaller space and time scales in Australia over issues such as sustainable water allocation in the Murray–Darling Basin or sustainable use of old-growth forests or fish stocks. As detailed in later sections of this chapter, we can learn from the use of quantitative scientific models in these smaller-scale questions to show us how to best employ models to address the larger global questions.

Quantitative models

Scientific models do not have to be quantitative, though many are. So long as they follow real-world constraints, qualitative (descriptive) models can still be internally consistent and scientific. However, for the purposes of this chapter we will focus on quantitative models.

Most quantitative models are sets of linked mathematical equations that encode scientific understanding of how nature or society operates. The real world is so vast and complex that building even highly simplified representations of it can be a major scientific enterprise. Large computer models that describe the evolution of oceans, atmosphere, sea ice and terrestrial ecosystems are used to predict weather and climate. On the other hand, very simple models of these same systems, consisting of just a few equations, can give important insights that may be lost in the detailed models. In practice, to maximise learning we employ models that span a range of complexity.

Finally, an absolutely fundamental attribute of scientific and quantitative models is that they must be explicit [16]. Their assumptions—the algorithms that encode the scientific understanding and the data behind the model inputs—must be clearly stated and available for scrutiny. This is a crucial difference between the models we will discuss in the rest of this chapter and people's internal world views and narratives whose assumptions are rarely exposed to the light of day.

2 What are models for?

Most non-modellers assume that the purpose of a scientific model is prediction. This is only one use of models, albeit an important one; Epstein [16] lists 16 reasons for modelling, apart from prediction. Even prediction can mean something quite different to scientists and the general public. The default assumption of most people is that a prediction involves a definite, deterministic statement such as 'A will happen and B will not', whereas science is used to predicting probabilities: 'There is a 65% chance of A happening and a 35% chance of B happening'. Probabilistic prediction, however, is becoming more familiar; for example most weather forecasts are now stated as probabilities.

When models represent the interaction of the natural world and society, prediction in any sense becomes much more problematic. The strongly contingent nature of human decision-making means that the exact form of the future is essentially unpredictable. This does not make models useless, however.

An important feature of such systems is that, although specific details are unpredictable, there may be a stable statistical spread of outcomes in the long term that have predictable average behaviours. It is easiest to characterise these behaviours if there is a broader context to the predictions. This context is provided by scenarios (internally consistent stories about how some aspect of the system, such as the level of globalisation, may evolve into the future) to which we can assign some likelihood or preference. Chapter 4 in this volume explores scenarios in much more detail, but the intersection of scenarios with quantitative models is illustrated well by Figure 3 (from [17]). This plot shows the evolution of global temperature to 2100 for four trajectories of greenhouse gas concentrations that correspond to scenarios of how the world's economy might develop, given plausible assumptions about rates of globalisation, economic development, the success or otherwise of global mitigation agreements and so on [18].

Quantitative modelling played two roles in producing this figure. First, we see that the temperature curves have bands of uncertainty. This reflects not only the fact that the climate has chaotic elements but also that there are some facets of the climate system we are unsure of or cannot model completely faithfully. Consequently, we can only predict a range of resulting temperatures for each greenhouse gas trajectory. Nevertheless, we can specify this range quite well and assign definite probabilities because the planetary dynamics that control the climate obey laws of nature and well-understood scientific relationships. Second, the scenarios of global economic development that lead to each projection of possible greenhouse gas concentrations are produced by integrated assessment models (IAMs), which contain descriptions of social processes like economics and demography. Although social processes are much more difficult to capture in quantitative formulae than physical ones, they are still bounded to some degree by the laws of nature as well as by other constraints such as path dependency (where making some choices about development paths excludes others).

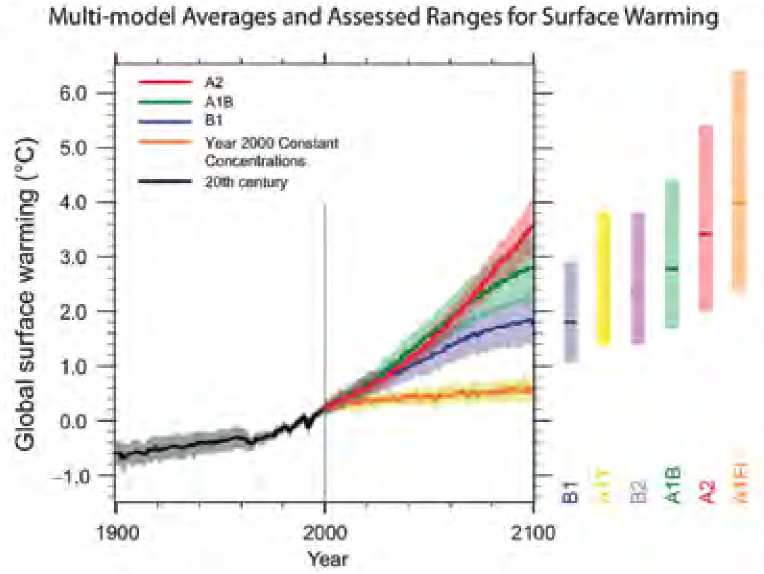

Figure 3: Trajectories of average global surface temperature to 2100 corresponding to scenarios of global development and their consequent greenhouse gas emission trajectories (shaded bands around the trajectories indicate one standard deviation of individual model averages). The bars on the right indicate the best estimate (solid line within each bar) and likely range assessed for six illustrative IPCC emissions scenarios (drawn from hierarchy of individual models as specified in [17]). Redrawn from Figure SPM-5 in [17].

Of equal importance to prediction is modelling to gain understanding. We can build models that reveal the essential processes behind observed phenomena without necessarily being able to predict their occurrence. For instance, plate tectonics explains the nature and location of earthquakes, but so far has not allowed us to forecast their occurrence. Similarly, over the last decade computer models of social networks have provided important clues as to how ideas, opinions and fashions spread through society without being able to tell us whether one idea is more likely to be adopted than another [19].

A third reason for modelling is as a test bed, to check the consequences of choices we may make as a society without suffering any dire consequences.

We have only one world, which means (for example) that we cannot compare the result of increasing greenhouse gas concentrations in the earth's atmosphere with the behaviour of a parallel world where the concentrations are held steady but everything else behaves as on the Earth[2]. Consequently, for most of the manipulations of the world's natural dynamics and societal relationships that humanity is currently performing, modelling is the only way we know to test the likely results or to explore alternatives. A fourth reason for modelling—one that is aimed squarely at the conflict between different world views—is to use models as a forum for wider social discussion. Models can allow us to compare the alternative futures that could result from choices we make today, and in the next few decades, without prejudice or priority being given to any one world view. In this way, the trade-offs, unintended consequences and constraints of any potential future can be explored. New ideas can be generated about how to deal with the many challenges now facing Australia and the globe. Used in this way, models can allow us to expand and anticipate the time and space horizons of our planetary boundaries. They can help us avoid the sleepwalking into disaster that has characterised almost all past encounters of human civilizations with natural boundaries of geography and resources.

Within the bounds of these four purposes for modelling there are many ways to use models to help us understand the dynamics of our world or to plan for the future. One of their most important applications is to define the reachable space within which society can make choices. Laws of nature and path dependency together mean that our past and present choices have already excluded a large number of potential futures; the remaining (constrained) set of possible futures are the reachable space. We can define this space because the physical world must obey the laws of nature (even if social choices are more unpredictable)

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[2] However, comparison of the Earth with Venus (runaway greenhouse effect) and Mars (negligible greenhouse effect) has been very useful in understanding this particular aspect of planetary physics.

so that the future consequences of choices made today are bounded. For example, the increase of almost 50% in atmospheric greenhouse gas concentrations since the start of the Industrial Revolution commits us to a climate warming of more than 1 degree Celsius, even if all emissions were to cease tomorrow (compare the end point of the flattish orange line in Figure 3 with the starting value in 1900). We can also make the form of this reachable space clear by spelling it out in terms of key indicators such as employment, affordable energy, water, healthcare, the state of the environment and so on. This use of the models is vital because these consequences are rarely obvious when we consider a complex system like Australia and Australian society.

A powerful new concept in applied modelling is to invert the concept of a reachable space and use modelling to define the boundaries of a 'safe operating space' for a society. The safe operating space can have biophysical, economic and social dimensions. Rockström et al [20] have discussed biophysical planetary boundaries defined by assuming that we wish to keep the planet's climate in a state close to that of the late Holocene, the climatic state in which all human civilization evolved. Defining the social and economic bounds of the safe operating space is a more difficult task [Finnigan et al., Chapter 9 in Volume 2] and will not be attempted here. Instead, potential classes of information required in determining a national safe operating space are listed in Table 1.

Component	Information types & attributes
Physical climate system	Temperature
	Rainfall
	Sea-level rise
	Extreme weather events (storms, extended heatwaves)
	Probability of large bushfires
	Ozone levels
	Ocean acidification (pH, aragonite saturation state)
	Nutrient cycles (soils & waterways)
	Water* (surface & groundwater)
	Aerosols (smoke, dust, industrial)
	Level of chemical contaminants
Ecological system	Land cover of different vegetation types
	Land use* (crops, grazing land, forestry, conservation, recreation, mixed & urban areas)
	Biodiversity (species distributions, extinction rates)
	Ecological community composition & structure
Social and economic	Wellbeing
	Inequity
	Income (levels, unemployment rates, employment diversity)
	Human capital (health, life expectancy, education, level of crime)
	Social capital (voluntarism, sense of community, harmony, resilience, quality of life, freedom of expression, spirituality, access to recreational pursuits & green space, place attachment)
	Infrastructure (transport, services)
	Housing (availability, homelessness)
	Cultural diversity (multiculturalism)
	Economic system (market-based, independent reserve bank)
	International trade (demand, exports, imports, exchange rates)
	Government (federal–state democracy, fiscal neutral policies, expenditure, taxation receipts)
	Resource state & production (renewable, non-renewable)
	Domestic demand (preferences)
	Demographics (population size, age, household, labour)
	Technology (efficiency, uptake)
	Emissions
	Policies

* These include the provisioning of humans with food and water

Table 1: Components of a future world that need to be considered when defining a safe operating space for Australia.

3 The contents of models

It is convenient to separate quantitative scientific models into four types: models of the natural world, economic models, social models and integrated models that attempt to bring features of all these together in a unified whole. In this section, we will briefly describe the history and modern developments of each type of model.

Natural world

There is a long history of modelling the dynamics of the natural world at different time scales: from the epochal time scales of geological processes, to the decades, to millennia over which climate is defined, to the days and to the hours over which we predict the weather. Along with these different time scales come different spatial scales, from the global to the regional to the local. Modelling the biophysical world is the area of application where natural science has hitherto been most comfortable and successful.

There are as many different kinds of biophysical model as there are different scientific disciplines. Within the context of climate change the best known are global climate models, or GCMs. These models (e.g. Australian Community Climate and Earth-System Simulator (ACCESS) [21]) are constructed using equations governing the large-scale circulation and thermodynamics of the atmosphere and oceans. They are continuously being improved and expanded to include more components of relevant processes such as the carbon cycle. GCMs are used to investigate the climate impacts of potential future emission scenarios and they produce global maps of ocean and atmospheric properties (e.g. temperature fields). The spatial resolution of these models is becoming finer all the time. The latest generation of GCMs resolves the entire globe at scales as fine as 50 km. Within Australia, ocean-forecasting models now resolve water movements and properties like temperature and salinity to scales of 10 km, with finer-scale models under development around the coast. Similarly, ocean–atmosphere models resolve Australia's landmass down to less than 4 km. Processes happening at scales finer than those the model resolves directly but which influence the resolved calculations through feedback mechanisms are typically represented by simplified relationships or 'parameterisations'. These are often empirically derived; for example those for cloud cover, convection or albedo. The outputs of GCMs are mapped on to finer scales for specific regions using finer-scale models that sit (or 'nest') within the larger model (e.g. Figure 4). These finer-scale models are then used to explore some of the regional implications of potential future environmental shifts, but are also used in more day-to-day assessments such as the fate of yachts lost at sea or the dispersal of air pollution.

The living components of the natural world have also attracted the attention of many modelling efforts. Land-use models are not only used to incorporate the influence of land surface processes (e.g. photosynthesis, evapotranspiration or hydrology) on climate, but are applied regionally to assess the implications of changing agricultural practices [22], catchment management [23] and urban or coastal development [24]. In the marine realm, models of habitats, food webs and entire ecosystems have been used to explore the implications of conservation and fisheries management decisions [25]. These ecological models span a wide range of process detail, depending on the questions they have been designed to answer. The most sophisticated include processes such as primary production, nutrient cycling and the breakdown of waste, movement, predation, competition, growth and reproduction.

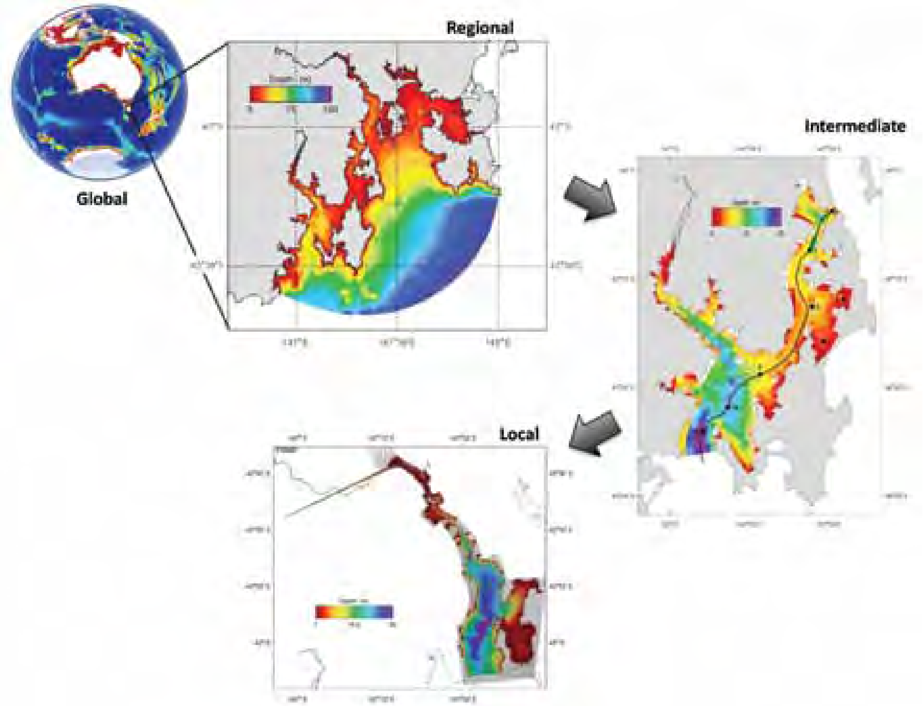

Figure 4: Example for the Derwent River region, Hobart, Tasmania, of downscaling from climate models to regional models—in this case of ocean properties (e.g. temperature, current flow etc.) for marine planning and management on finer scales (modified from [26]).

Economic systems

Economics—perhaps the most quantitative of the social sciences—is also a discipline comfortable with modelling. There are economic models focused on the many different aspects of the economic spectrum. Macroeconomic models address the entire global economy or deal with naturally coupled subsystems such as energy or agriculture. Models of market behaviour are used to try to understand the unpredictable and stochastic behaviour of trade in all sorts of commodities. Financial or 'fiscal' models are tools used by treasury departments to assess the impacts of taxes or regulations on national accounts. The increasing use of models to perform risk analysis or to automatically guide share market investment has become widespread. This last application of economic modelling has attracted a great deal of criticism in the wake of recent market booms and busts [27, 28]. Unlike models of the biophysical world, economic models are not based upon fundamental laws of nature and therefore need careful application and interpretation to avoid being misused.

Macroeconomic models (with assumed internal microeconomic behaviour) are perhaps the most common form of model currently used to inform policy decisions in Australia. They can cover the entire economy, when they are referred to as computable general equilibrium models, or just part of it, such as the agricultural or energy sectors, when they are termed partial equilibrium models. At their largest these models are dynamic, multisectoral (covering more than 50 industries) and multiregional (spanning all Australian states). They are used to explore interacting regional economies and the effects of technology and policy decisions on competitive markets, labour and capital flows and household consumption [29]. These models can be coupled with other aspects of the system (e.g. models of international trade, changing resource productivity) to form the basis of IAMs. (discussed further below).

Agent-based models[3] (e.g. where individual components of trading networks are tracked through time) have also been used in economics [30], but are not nearly as widespread as equation-based general equilibrium models. To date, agent-based models have focused more on microeconomic decision-making than macroeconomic processes, but this is starting to change. However, in combination with social aspects of the system (discussed below) agent-based models can explore behaviours outside the realm of the classical CGE models and so are likely to also find a place among the suite of models required to fully explore and communicate the implications of alternative futures.

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[3] Agent-based models compute the behaviour of many interacting individuals or small groups and how they change through time and allow their average behavior to 'emerge'. This is in contrast to analytical models that solve equations for aggregate or average behaviour directly.

Social systems

Modelling is less common in the rest of the social sciences. This is in part because it has been argued that human behaviour is too unpredictable or involves too many influencing factors to be predictable [31]. However, approaches to simulating social dynamics taken from complex systems science, such as agent-based modelling and network theory, are changing this view [32; Finnigan et al.,Chapter 9 in Volume 2]. Quantitative models of social systems have been used to explore information sharing [33] and innovation [34], decision-making under social constraints [32], and to explore a range of issues, including drug use [35], crime fighting, traffic flow, marriage rituals and the segregation of neighbourhoods [36]. Nevertheless, a significant gap remains between such conceptual models, used to gain insights into real-world systems, and applications of these principles in models of direct interest to businessmen, government policymakers or the general public.

Integrated models

In the last decade-and-a-half a new, more integrated modelling approach has developed that links models of the natural world, economics and social dynamics to produce IAMs. To date these have been applied primarily at two spatial scales, the global and the regional. The missing scale is the national scale, the one that particularly concerns us here. National-scale models are largely in their conceptual infancy [37] and require some processes and properties (e.g. dynamic governance or policy-industry-environment feedbacks) not typically included at either the regional or global scale.

The earliest IAMs were applied at global scales in the 1970s [38], but their use intensified in the 1990s [39]. Most global models of this kind have been used to project greenhouse gas emissions (e.g. the scenarios used by the Intergovernmental Panel on Climate Change (IPCC)—the emission trajectories leading to the different coloured lines in Figure 3) and to consider the welfare and economic costs of alternative trajectories (which is what policymakers have typically asked about most). IAMs seek to couple human behaviour, as represented by socioeconomic determinants and policy, with the behaviour of the atmosphere-ocean-climate and living ecosystems. The aim is to deduce the biophysical and socioeconomic impacts of human behaviour as well as possible societal and biophysical responses. Broadly speaking, they compute the impacts of changed climate—for example, temperature and rainfall changes, on agriculture, industry, human health and other components of the economy. They then work out how the resulting changes in economic activity alter the emissions that drove the changes in the first place, thereby coupling the climate and economic components of the Earth System (Figure 5a). The first climate-related IAMs were only vertically integrated, following the chain that links the causes and consequences of climate change (Figure 5b). By 2000, horizontally integrated models (Figure 5c) were being constructed to assess what might constitute sustainable development; these models had an enriched structure with more complex linkages and feedbacks, such as direct human modification of ecosystems and CO_2 fertilisation of plants, yielding more complex structures.

* Conditions include atmospheric, terrestrial and ocean properties (e.g. temperature or rainfall).
# Direct impacts cover impacts to natural ecosystems as well as cultivated crops and forests.

Figure 5: Schematic diagrams of IAMs: **a)** the general concept of the model structure that includes both climate and economics; **b)** vertically integrated models (which are effectively one-way flows); and **c)** more interconnected horizontally integrated models. These figures are modified from figures in [39, 40].

At regional scales, dynamic fully coupled models of the entire system have been in existence since the 1970s, though they have really only come into relatively common use in the last 15 years as computing power has reached a point where their use has become tenable. Early models (e.g. of resources associated with rivers or lakes [41]) often exceeded available computing power and largely fell out of favour until the 1990s. Since then they have incrementally regrown, from multispecies (predator-prey) and primary production (plant or plankton) models to models that include regional-scale physical factors (and exogenous large-scale environmental forcing), much of the food web of a region and some representation of the dominant human activities [42]. Within the marine realm these models can now span processes, from the micrometre scales of bacteria to tens of thousands of kilometres (for ocean basin or global scales), and processes that act on seconds to centuries. Somewhat surprisingly, modelling terrestrial dynamics at an equivalent level of complexity has lagged in practice in the aquatic domain, but this situation is now being redressed [43]. This means that there is already some solid experience with the kinds of challenges that will be faced when building national- or continental-scale models.

Dealing with model uncertainties

Building fully integrated system models pushes scientific understanding to the limit—not all processes are equally well understood and new ones are uncovered as the models are put together and gaps are identified. It also pushes the bounds of complication (i.e. the size of the models and the number of parameters) and complexity (feedbacks and non-linear system behaviour). This can make these models uncertain and potentially difficult to work with.

Although experience with quantitative modelling is least well-developed for social systems, where uncertainty is greatest, in truth there are uncertainties in all the domains. However, the presence of uncertainty should not lead to inaction; risk is about the weighing of the likelihood of an event occurring and the impact it may have if it does. Issues in the real world may become more pressing and difficult to remedy if precautionary action based on risk assessment does not occur. Likewise, uncertainty should not see the abandonment of models, as science has over 50 years of experience with how to deal with such uncertainty.

Three main sources of uncertainty are dealt with on a regular basis by scientific modellers. First is the uncertainty associated with the trajectories of a dynamic, or chaotic, but well-characterised system—this is reflected in confidence bands around mean trajectories, like those presented in Figure 3.

Another aspect of uncertainty has to do with the future state of properties we know to be important but have no way of projecting with confidence. Future political and societal decisions, such as those regarding policies and behaviours around emissions levels, are an example. These decisions will have a substantial impact on the factors that influence the Earth System by the end of the century, but we have no way of knowing now what they will be, and there are very many options. This kind of uncertainty can be represented by 'what if' scenarios—illustrated by the different scenarios and resulting bands of potential outcomes presented on the right of Figure 3. The importance of these first two kinds of uncertainty can also be different as we move further into the future. For instance, the uncertainty about near-term climate states within the next couple of decades is mainly a result of the chaotic nature of the biophysical system. While there is a small degree of uncertainty about exact values, in broad terms fundamental physical laws and inertia in the system mean the trajectory is actually fairly well-constrained. This is why all of the trajectories for the different scenarios in Figure 3 have a good deal of overlap until 2020–30. After that point, however, uncertainty about the social and regulatory responses comes to dominate, leading to the large deviations between the ranges of outcomes in the long term (e.g. compare B1 and A1F1 in Figure 3).

Lastly, there is uncertainty due to gaps in knowledge about the system—processes that are poorly known or even ones that we do not realise exist as yet. Operationally, we can deal with this kind of uncertainty by building models incrementally (as mentioned above for the integrated models), adding new components as new information on connections or processes becomes available. A complementary approach is to use multiple alternative models to capture different ideas of how the system works, and examine the implications of each of the alternative forms under all of the suggested potential future developments or policies. If the outcomes are effectively the same across a range of model representations, then there is increased confidence in the robustness of the conclusions drawn. The IPCC provides guidelines around how to express this confidence—from 'low' when there is limited evidence or low agreement between experts through to 'high confidence' when there is a lot of rigorously examined (robust) evidence and high levels of agreement [44].

Even if uncertainty persists and the outcomes are different across alternative model representations, the range of resulting outcomes can still be used to provide information on the range of potential future scenarios that must be considered. These scenarios can in turn be used to paint broad contexts for management decisions—and models—at smaller scales that recognise the uncertainty at the larger scale.

There is a tight relationship between scenarios and models when both are used to their best effect. Scenarios can provide context for a model, effectively saying 'if the part of the world you can't represent in the model does this, what would be the response of all the bits you can model?' Models can ensure that the broader pictures of the future that scenarios help to paint are internally consistent and not in breach of natural laws. Chapter 4 in this volume provides a detailed discussion of four potential future scenarios for Australia. In addition, some contextual geopolitical scenarios are provided in Table 2. These kinds of scenarios would dictate assumptions about trade, spending patterns, competition for resources and so on that would be included in any national-scale integrated models.

Climate drive threatens SE Asia: There is increasing demand for water due to growing populations and industrial expansion. Changes in regional climate could contract the water supply and make it more variable. China has a 2000-year history of water-control programs and controls the headwaters of major rivers feeding India, Bangladesh and SE Asia.

Least violent outcome	Business as usual	Most violent outcome	Implications for Australia
All the nations in the region agree to basin-wide sharing and allocation of water. Simultaneous improvements in efficiency of water use.	China continues to steadily divert more water from SE Asia into water-poor regions of China (likely refraining from redirecting waters destined for the subcontinent for diplomatic and security reasons). Even if SE Asia can improve efficiency, rise in tensions is likely.	China aggressively diverted water from all the headwaters to its water poor regions. Significant tensions arise between China and both India and Vietnam (possibility of war and nuclear exchange).	Level of instability affects Australia's trade, productivity and border security (massively increasing people movement and refugee pressures).

Table 2: Potential geopolitical scenarios that could be used as context for a national-scale IAM. Note that these are not forecasts, simply alternative views of how the world may unfold.

Unification of the Muslim world:

Many pressures for change in the Middle East and Africa (fast-growing populations, millions of unemployed youth, education gaps, a rejection of modernism and the West due to past support for local dictators). Many different unifying concepts proposed (e.g. democracy vs. religious caliphate, many antithetical to Western powers).

Presence of nuclear weapons programs could exacerbate nervousness of other nations (e.g. Israel) regarding the outcome.

Least violent outcome	**Business as usual**	**Most violent outcome**	**Implications for Australia**
Israel and the USA may take decisive (and early) action to neutralise the nuclear threat, simultaneously preventing accommodation between Shia and Sunni interests and supporting key oil-producing Arab states so that they do not participate in any aggregate body (or caliphate).	Not all Muslim states (or key oil producers) fall, so smaller aggregate body formed. Heterogeneous make-up of the Muslim world. Israel may still destroy Iranian nuclear facilities and Pakistan may still suffer at least partial collapse, particularly in the north where large bandit regions of Taliban may form.	Broad geographic caliphate forms. Nuclear exchange between Israel and Iran disrupts global oil production; antiMuslim sentiment leads to suppression of Muslim minorities in China, Russia and Europe. Potential US pre-emptive strikes on Pakistan's nuclear stockpile; stand-off with India (over weapons) leading to Indian push into Kashmir and Afghanistan, resulting in a further stand-off with China (which may support Pakistan and enter Afghanistan against India).	Some trade implications. Could cause shocks to fuel supplies and large-scale people movement.

4 What models can already tell us about the future

While national-scale integrated models do not yet exist, quantitative models of component parts of the Australian system are already being used to give some indication of what the future might be like in Australia if we continue as we are—a scenario often described as ‘business as usual’—or switch to other management and development options. A full exposition of all available model outputs would take a book in itself. In lieu, an illustrative summary of projected futures for many aspects of the Australian system is provided in Chapter 6 of this volume. Further discussion of projections of some aspects of Australian society and industry also appears in volume 2.

5 The importance of broad participation in the modelling process

To date, communication of scientific knowledge of climate change and what is causing it has not been universally successful. As a result, there has been confusion surrounding the topic in the community as a whole and full use of the information has not always been made in decision-making. This has led to tension between people with alternative views on the topic and has also led to a sense of bewilderment and frustration about why it can’t be clearer. This confusion and frustration has come about, at least in part, because of an assumption held by many physical and environmental scientists that simply delivering additional information is sufficient to provide understanding and cause behavioural change. Experience in natural resource and coastal management as well as social and behavioural research and sustainability science has found this approach is actually largely ineffective [45], and can even harden existing opinions [46,47].

Learning, and any resulting behavioural changes, are a product of complex cognitive and social processes [48, 49], all of which are enhanced by free and open dialogue, trust, airing of conflicting viewpoints, participation, sharing of control and responsibility, direct experience and reflection [50]. Knowledge is also distinct from information. Information is interpreted data and factual statements [51]. On the other hand, knowledge, much of which is tacit and unspoken [52], is the capacity to act effectively, which is rooted as much in experience, contextual bounds and social values as it is in supporting evidence [53]. This makes effective knowledge transfer much harder than is naively assumed [54].

So far in this chapter we have described three reasons for the value of modelling: for prediction, to gain understanding and as a test bed. Our fourth reason for modelling introduced the idea of participatory models as forums for discussion and the resolution of competing ideas. Using models in this way brings together the concepts of scientific modelling and innate world views and uses all kinds of models, from the simplest representations to the most detailed. Shared storytelling and conceptualisation of problems are features of all human cultures, and models can be used as a framework for discussions, to formalise and channel these activities to help communities find solutions to divisive problems, even when different members of a group hold conflicting objectives. This approach has been used successfully in a broad range of areas; for example at regional scales to address the management of natural resources (such as fisheries [55], catchment management [56], integrated coastal zone management [57]), and social challenges (e.g. inner-city drug use and prostitution [35]).

Experience with applying participatory processes that are anchored by scientific models (not just world views) has shown that, like a system of interconnecting cogs (Figure 6), the approach leads to the democratisation of knowledge and can build understanding and elicit options and opinions from a broader spectrum of the community and lead to more effective governance. It is a means of bringing together expert advice (e.g. scientific, ethical, technological, or economic) and community-held world views to both educate and be educated by the process. Furthermore, any actions taken are more robust, because the inclusive nature of their germination means all parties feel ownership and there is greater compliance, as the need for hard decisions is recognised and steps are taken together rather than being imposed by one body on another. This participatory approach also supports more adaptive management, as new perspectives or suggestions from experts, governance bodies and the community can be fed back into the models, either to update them with new information or to investigate the potential outcomes of the new alternatives. The models become the common arena for discussing ideas; an arena that is not static but can evolve with new understanding and new ideas, forming the foundation for ‘living scenarios’ as described in chapters 1 and 4 of this volume.

For a ‘living scenarios’ approach such as that just described, to succeed there must be trust in the tools used to define the scenarios. In the rhetoric presented in the media around debates on topics such as the use of shared resources like the Murray-Darling Basin, positions based on science and the use of models are often attacked and misunderstandings over the use of the models – or open distrust – are often clearly evident. One of the sources of this distrust is a lack of exposure to, and experience with, models. It is an often-heard statement that ‘I’m not a modeller, just a simple <insert profession of choice>. This perception is typical

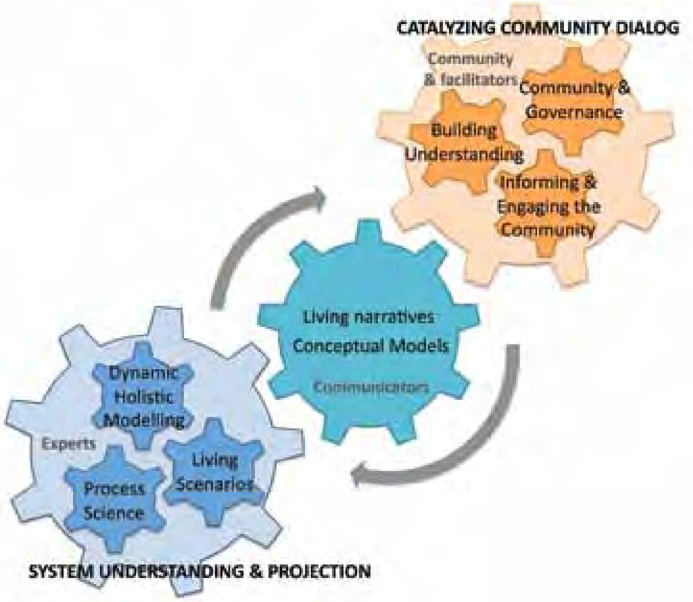

Figure 6: A schematic representation of the interconnected processes that can be used to plan alternative futures. At the lower left there is the science-based foundation, using observationally and theoretically based understanding to build models to make projections of the future given constraints of human behaviour, social institutions, development objectives, resource use, technologies and policies.
This understanding is shared (communicated) more broadly using stories and simpler conceptual models. The resulting dialogue (upper right of the diagram) may also be based around models of different forms (from purely conceptual to more quantitative), supporting understanding and engagement as well as feeding into governance. Ultimately, these feed back to the dynamic system models in the lower left (both in terms of updated scenarios via increased understanding of the human dimensions of the system and how they may respond, which can be explicitly incorporated into the models).

because people are unaware of how they themselves use models, particularly mental models, to make decisions. One way of simultaneously increasing this awareness and providing an explicit sense of familiarity with the use of models is to provide people with an opportunity to directly interact with them. Simple models stripped to the essential basics of system function can offer a means for anybody to interact them from their definition (i.e. identifying what should be included) through to hands-on exploration. This can help people appreciate the strengths and limitations of models (they are not crystal balls). Moreover, these simpler models provide the means for people to explore via direct experience a version of the system and so gain a deeper appreciation for how the system functions and the way feedbacks can lead to unexpected outcomes or delays in actions. This kind of understanding increases the willingness to use models to help frame discussions around alternative futures, societal objectives and what are acceptable levels of impacts. Models can also supply a means of gaining experience with how complex systems respond when put under stress, helping to accelerate the evolution of intuitive mental models and making them more useful in the modern world [Boschetti et al, Chapter 8 in Volume 2]. Moreover, they provide a means for individuals to explore the strengths and weaknesses of their world views and, as a result, potentially modify them.

The transparency provided by simpler models must be maintained when using more complex models to make projections about future system states to inform regulatory bodies and policy makers. Economic (and other) models are already widely embedded in governance. For broader, more inclusive system models to be used the same way they must be transparent and interpretable, so that the credibility of their outputs can be judged based on an assessment of their key assumptions and their ability to represent critical processes. Additionally, the models must provide information to decision-makers in forms they are already familiar with and with absolute clarity—an ill-posed framing can unintentionally constrain direct model-based conversations (e.g. ignoring potential costs associated with a business-as-usual scenario and overlooking the opportunity for benefits under alternative policies).

Before moving on to sketching how such a participatory model-based process might be implemented at a national scale, it needs to be stressed that this approach is not something that flows only in one direction (as shown in Figure 6). It is intentionally a two-way interaction. While allowing for broader understanding of systems, it also facilitates an information flow back to system modellers on missing components of the system. Of all the parts of a social-ecological system, the parts that are most difficult to model at present are those dealing with human behaviour. However, the responses and adaptations of people within a system will almost certainly be a key component of its future direction and degree of resilience. By watching how people from a broad variety of backgrounds (and cultures) make decisions when exploring simpler models, scientists can build new understanding. This new information can be used to further refine or expand the system representation captured in more complex models or as the basis for new sets of contextual scenarios to consider—either broadening the options to be explored or identifying where choices may more firmly lock society into a more constrained set of future paths.

6 Making national-scale modelling real

While participatory approaches have seen widespread use in many Australian jurisdictions, a national-scale engagement process of the kind envisaged here would not necessarily be easy. While similar approaches have been highly successful at local or regional scales, such as in the Ningaloo–Exmouth region of the Gascoyne, Western Australia [57], a national-scale effort faces new challenges.

The most obvious challenge is building the models that will form the basis of the approach, both the underpinning models and the models for use in the engagement process. While a full implementation of the participatory approach means that a broad audience should be consulted to determine key system components, existing experience affords us a good idea of the scope of the models and likely components (Figure 7). While simple models of this system could be drawn up fairly rapidly, in terms of a complex IAMs no such model yet exists at a national scale. As mentioned previously, models with similar conceptual breadth of scope have been applied at regional scales and are beginning to be implemented on a global scale [59]. Experience from these other models shows significant scientific and computational challenges will need to be met to incorporate the new processes before a complex national-scale IAM is a reality. Taking these lessons on board, research organisations have prototypes under construction.

Figure 7: A diagram illustrating likely required components for a national scale IAM.

If the kind of living scenario approach discussed above (and elsewhere in this volume) is to be implemented nationally, building the models is only one aspect of the challenge. Another pressing problem will actually be how to be participatory at a national scale. There needs to be further reflection on past experience at broader scales (e.g. by state governments) and whether it is a concept that remains appropriate at such broad scales. We can also look to experience in the private sector. Even if it is concluded that the method is valid, then seeking individual involvement in the process of defining the model components, specifying desirable system states and participating in ongoing iterations of model evaluation and refinement is not feasible at national scale. It is not actually feasible even at a regional scale for all but the most-sparsely populated areas of Australia's interior. Fortunately, Australia's historical handling of natural resource management can provide insights into what a framework for successful participatory engagement at a national scale might look like.

As acknowledged above, participatory approaches to decision-making have been used in many Australian jurisdictions. An example of such a process that is successful on very large scales (beyond regional and state scales) is the hierarchical consultation process at the heart of Australia's federal fisheries management. The *Fisheries Management Act 1991* requires management in accordance with the long-term sustainability of Australia's fisheries resources for the benefit of all users and interest groups both now and in the future. In turn, this entails actively cooperating and consulting with fisheries managers, scientists, industry, government agencies and other interested groups in the process of developing and implementing fisheries management arrangements. This consultative process raises awareness of fisheries management issues while also providing opportunities for direct input and (critically) a sense of ownership in the fisheries management decision-making process. This level of consultation is possible because managers within the Australian Fisheries Management Authority (AFMA) are advised by management advisory committees (MACs) and resource assessment groups (RAGs), which have been established for each major federal fishery. MACs offer a broader perspective on management options, providing a forum to discuss fisheries issues and possible solutions. MAC membership is quite diverse and includes an independent chairperson, an AFMA manager, a research scientist, up to four industry representatives and an environment or conservation representative (e.g. someone from the Department of Environment or a non-government organisation (NGO)). Increasingly, MACs also have members representing the interests of state governments, recreational fishers and charter boat operators. RAGs also have broad membership, comprising fishery scientists, industry members, fishery economists, management and other interest groups. The intentional breadth of this membership ensures that scientific information (on the status of stocks and marine environment more generally), industry knowledge, compliance factors and economic data (market prices and the costs of harvesting) are all taken into account when discussing management strategies. Ultimately, RAGs provide advice to the MACs and AFMA explicitly stating uncertainties and risks associated with alternative management options. A particularly important point about RAG meetings is that they are open to anyone who is interested. While this degree of openness may sound like a recipe for chaos, in practice it is quite functional and the individual level of understanding of the issues has become quite high (e.g. fisherman have an understanding of what stock assessments contain and how to interrogate them to check their veracity and degree of uncertainty). This kind of collaborative participation in resource management is known as a form of co-management [58], and while it does not guarantee consensus, it does allow for effective utilisation of different forms of knowledge.

In Australia, a hierarchical means of delivering information to decision-makers is not unique to fisheries. Advisory councils presiding over matters of the environment, agriculture, fisheries, forestry and regional planning have a long history (e.g. the Australian Agricultural Council was founded in 1934. In 2000, the various councils were amalgamated to form two bodies, the Natural Resources Management Ministerial Council and the Primary Industries Ministerial Council). This means that precedents on the means of delivering the output of living scenarios already exist. It is only the scope that needs to be expanded.

A review of co-management initiatives from around the world [60] has identified some key conditions for success (summarised in Table 3). Chief among these is that representation must be appropriate given the environmental, population and management scales of the resource to be managed, while remaining small enough to be workable. At first glance this sounds impossible at a national scale, but Pomeroy et al [60] highlight that to meet the conditions for success inherently requires planning and implementation at several mutually supportive levels: local, community, cross sectoral and overall. As prototypes already exist for governance and sectoral participation, the most significant remaining gap pertains to the selection of representative delegates at lower scales who can take the outcome of the interactions and discussions and communicate them to a broader audience still (ideally the entire community). It may be possible to use well-established social and psychology tools (e.g. egoNets [61]) to identify delegates who can be the community contacts. For maximum effectiveness, these delegates should include representative individuals for different groups in the system and key communicators or people who connect many parts of the system together. A broad representation will be fundamental to the inclusiveness of the process, with the models acting as an honest broker, facilitating conversations among groups that may have conflicting viewpoints or objectives. Beyond the engagement with delegates, communication with the broader community will likely require ingenuity and effort, exploiting old and new technologies alike (e.g. from collaboration with television programs or documentary makers, to immersive gallery exhibitions, online games or more formal methods from social science and psychology, such as psychometrics, which have been used to increase awareness of sustainable water policies [62]).

Scale	Conditions affecting success
Supracommunity	Enabling policies and legislation Facilitators (help objectively define the problem, supply expertise).
Community	Appropriate scale and boundaries (representative, but not too large). Group connections (e.g. kinship, ethnicity)—not an absolute requirement (many examples where diversity was not inhibitory). Participation of those affected. Local leadership (or champion). Empowerment and capacity building. Community organisations (to legitimise participation of delegates). Cooperation of government and the powerful. Adequate financial resources. Active participation and sense of ownership. Accountability. Conflict resolution mechanism. Clear objectives. Enforcement & compliance.
Individual and household	Individual incentives (economic, social and political) to participate.

Table 3: List of conditions associated with successful co-management (from information in [58]).

7 What if we had tried this 40 years ago?

In thinking about the utility of the living scenarios approach, it is instructive to wonder how well it would have performed if we'd had the knowledge and technology to apply it in the past. There are two aspects to this. The first regards how well the models could have forecast the trajectory the world actually took. The second is whether an adaptive, participatory approach based on holistic models would have seen us follow a different path.

The first question is easier to address. Many of the models discussed in this chapter can be used to create a range of potential futures. If we had applied them in the past, it is possible that within the spread of projections was a trajectory fairly similar to what actually occurred. The reason it is possible to say this is that, in terms of the dynamics of the biophysical world, the models are reasonably robust. It is harder to capture social and economic dynamics, but even if these had been loosely specified by contextual scenarios then it is likely that the resulting trajectories for climate and natural resources like water or fisheries would have been sufficiently similar in form to what actually occurred to have usefully informed decision-makers. The evidence for this is that one of the ways climate models are used is to show that the observed trajectory of temperature is only possible if human emissions are included as inputs to the system. If the models didn't work, this test wouldn't work either. Moreover, we have the benefit of looking back and seeing how well simpler models applied in the past performed. The Club of Rome attempted to explore limits to growth over 30 years ago. At the time, the study was dismissed by mainstream economists, but recent retrospective analyses [63] have shown that what has actually happened over the last 30 years sits well within the envelope of possible outcomes forecast under the range of scenarios they considered (e.g. Figure 8).

More finely resolved details about specific aspects of the system sitting within such large-scale trends are harder to forecast. Technology is represented in the models, as are economic drivers and demographic structure. This means that in some trajectories something akin to shrinking family sizes and greater female participation in the workforce may have been forecast. By implication, this would necessitate the development of a childcare industry. However, if the model made no allowance for such a development ahead of time then it would not necessarily identify that such a thing would happen. Model processes may combine in unexpected and novel ways leading to unforeseen outcomes, but they are not capable of predicting everything, and especially not in detail. Technological parameters inside the models used as the basis for the original Limits to Growth analysis may be matched to advances in computing and, by taking a global perspective, they effectively incorporated aspects of globalisation. It cannot be said, however, that the models captured the social transformations being wrought by the internet.

The second query about how things may have worked out differently is much more difficult because we cannot go back and replay history. Given the models recreate global dynamics as well as they do, we could explore how things may have gone differently by changing parameters or performing specific interventions. In some ways this is what the original scenarios already do, much as the low-emissions scenarios of the IPCC do for climate simulations, showing what may happen if mitigation measures are put in place. More concretely, however, we can look to how trajectories have changed in other instances where adaptive participatory management has been employed. For example, in 2004 the Southern and Eastern Scalefish and Shark Fishery was facing declining economic and ecological performance as a result of overfishing. Previous management interventions had been unsuccessful and there was general agreement that management directions needed a rethink. Drawing on suggestions from managers, industry, scientists and NGOs, a broad set of scenarios was drawn up and evaluated (qualitatively and quantitatively). The range of options included business as usual as well as more stringent regulations, large-scale spatial closures and a form of mixed (or integrated) management that was so different from the existing management arrangements that the scenario was actually called ‘blue skies’. The unexpected outcome of the analyses was that the blue skies option actually met social, economic and ecological objectives best in the long term, though at the cost of severe short-term disruption to the fishery. These results were only one source of information used by managers to address the fishery’s problems, but it is noteworthy that many of the significant changes to the management of the fishery that were enacted in 2005 are elements of the blue skies scenario. It is hard to measure the direct influence of the analysis on the subsequent decisions, but the study did seem to capture the imagination of a range of stakeholders and act as a catalyst for significant change that put the fishery in a more robust position for dealing with subsequent shocks such as the global financial crisis, fuel spikes and shifting climate patterns. Based on a comparison with the rate of regulatory change in other fisheries, such rapid change would have been unlikely without a well-developed, participatory fishery management system [25].

Conclusions

The social norms, financial systems, institutional structures and so on that define society today are a result of past decisions taken in response to short- to medium-term pressures. The evolution of society has, by and large, been without regard for the strategic future. As a result, we have no guarantee that these norms and institutional structures are appropriate for the future. The challenge for science is to produce holistic representations of the world and its possible futures so as to identify community (private and public) policy options that are inconsistent with community and environmental resilience in the longer term. This means that the current state of society may not be appropriate if conditions change. When shaping policy pertaining to national issues and challenges associated with our collective future, it is important in a healthy democracy for the community to have the means to contribute to the development of alternative policies. People of all walks of life must understand the implications of proposed policies, what those policies require of them and what effect their implementation will have on their world. Without such understanding it can be easy to assume people and the system will behave as expected but for reality to play out very differently.

Models of all forms are already an everyday part of living. Quantitative models are being used to give insights into what the future may hold and are deeply embedded in government decision-making (e.g. treasury forecasts). The development of strategic integrated models that look forward decades at a national scale can support discussions of shared visions of potential futures that are consistent with society's values and the biophysical reality of the planet. In turn, this allows for planned formation of policies that include a sense of the long-term objectives. The models will need to provide sufficiently clear guidance that is regularly updated as both the modelling and what constitutes a preferred space evolves. This aspect of the living scenarios concept will not be easy at a national scale, but if it proves as effective as it has on smaller regional scales then it has enormous potential.

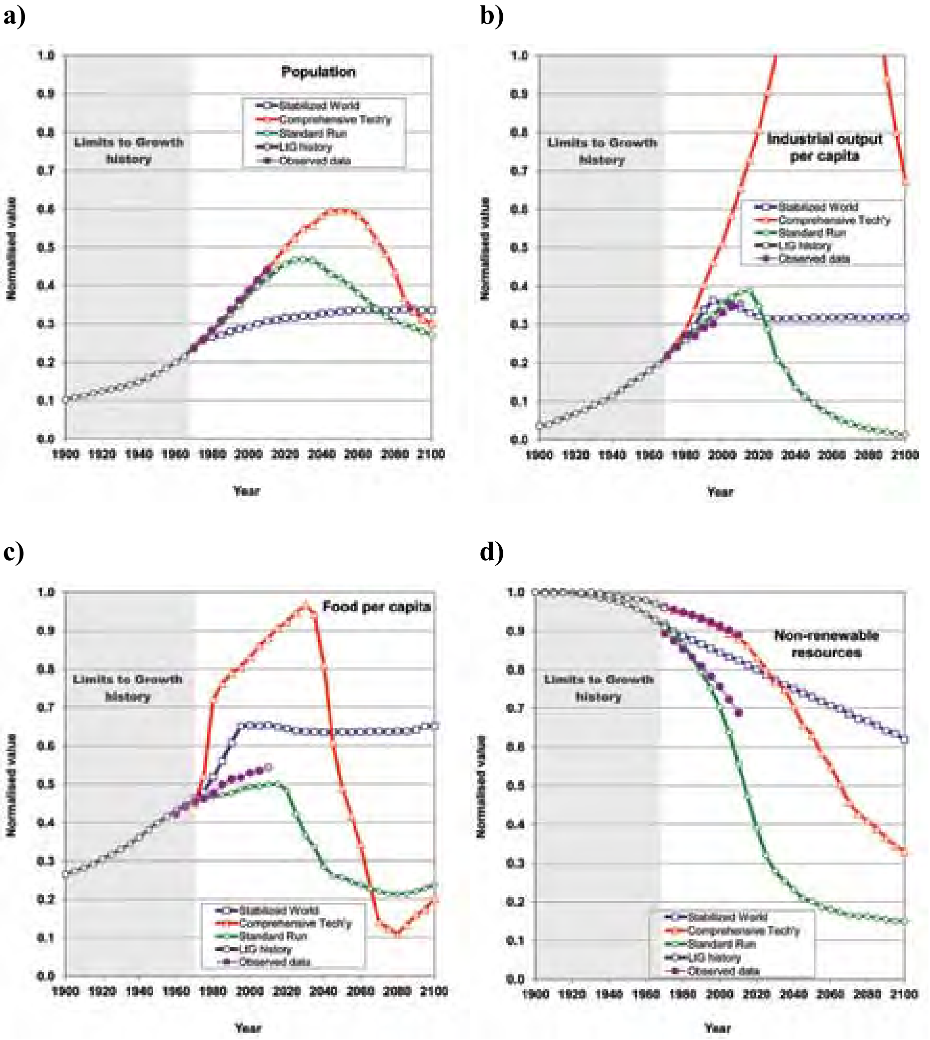

Figure 8: Comparison of Limits to Growth model projections and observed data for **a)** population, **b)** food per capita, **c)** industrial output per capita and **d)** non-renewable resources remaining (as of [62]).

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