Chapter 9

Quantitative modelling of the human–Earth System a new kind of science?

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The five grand challenges set out for Earth System Science by the International Council for Science in 2010 require a true fusion of social science, economics and natural science—a fusion that has not yet been achieved. In this paper we propose that constructing quantitative models of the dynamics of the human–Earth system can serve as a catalyst for this fusion. We confront well-known objections to modelling societal dynamics by drawing lessons from the development of natural science over the last four centuries and applying them to social and economic science. First, we pose three questions that require real integration of the three fields of science. They concern the coupling of physical planetary boundaries via social processes; the extension of the concept of planetary boundaries to the human–Earth System; and the possibly self-defeating nature of the United Nation's Millennium Development Goals. Second, we ask whether there are regularities or 'attractors' in the human–Earth System analogous to those that prompted the search for laws of nature. We nominate some candidates and discuss why we should observe them given that human actors with foresight and intentionality play a fundamental role in the human–Earth System. We conclude that, at sufficiently large time and space scales, social processes are predictable in some sense. Third, we canvass some essential mathematical techniques that this research fusion must incorporate, and we ask what kind of data would be needed to validate or falsify our models. Finally, we briefly review the state of the art in quantitative modelling of the human–Earth System today and highlight a gap between so-called integrated assessment models applied at regional and global scale, which could be filled by a new scale of model.

1 Introduction

The International Council for Science (ICSU) visioning process has led to the definition of five grand challenges for Earth System science [1]. At the heart of these challenges is an assumption that we can understand and possibly model the dynamics of the coupled human–Earth System—the intersection of the natural Earth System and human society. A signal benefit of this would be the ability to construct a compelling quantitative narrative of global change. The Australian Research Council's (ARC) Learned Academies Special Projects Australia 2050 project wrestles with the consequences of global change for Australia. We need to know, therefore, just how far quantitative modelling can take us in understanding the possible or likely trajectories that the social-ecological system that is Australia will take through the 21st century. In this paper we will try to make the case that quantitative modelling can profitably take us further than is conventionally assumed.

In the Anthropocene [2], Earth System Science (ESS) must be approached as a true fusion of the social, economic and natural sciences. However, ESS must then confront the problem that these three disciplines are at quite different stages, both practically and epistemologically, when it comes to quantitative modelling. The history of natural science is well known and libraries are devoted to it. It has at its heart the possibility of testing hypotheses against observations rather than by appeal to pure reason, an idea often traced back to Roger Bacon in the 13th century but which flowered in the Enlightenment and is now understood as the 'Scientific Method' [3]. This primacy of empirical falsification has been the means by which science has made the modern world, although it is also true that in practice the ideals of the scientific method sometimes take time (even generations) to have effect [4]. Despite this, natural science now has a robust set of fundamental laws of nature which serve as the scaffolding for quantitative modelling.

The social sciences cover a very broad field and most of the disciplines involved do not subscribe to the scientific method as a guiding principle (at least as it is defined above). Those that do are sometimes termed the positivist[1] social sciences and their origins can be traced back to the 'social physics' of August Comte and the developments of sociology as a science of society by Weber, Durkheim and Marx in the early 20th century [5]. Pinker (2002) [6] has argued strongly that areas of the social sciences consciously ignored empirical falsification in the last few decades of the 20th century, eschewing especially ideas and evidence coming

1 Wikipedia defines Positivism as a set of epistemological perspectives and philosophies of science which hold that the scientific method is the best approach to uncovering the processes by which both physical and human events occur.

from evolutionary psychology. While, over the past 15 years there has been a good deal of constructive engagement between social scientists and modellers using complex systems science approaches, it remains true that much of even positivist social science seems averse to the kind of generalisations that lead to the laws of nature that natural science relies upon. Instead, it is often claimed that human foresight, intentionality and reaction to the results of any forecast are insurmountable barriers to modelling social dynamics. We will confront this objection in §3 and §6 below.

The most quantitative branch of social science is economics, a discipline sufficiently rich that it is best regarded as a separate field. Economics also has two broad manifestations: normative economics, which is concerned with philosophical principles for organising the economy (and in recent times other aspects of society too), and positive economics which seeks to explain the dynamics of economic processes. Positive economics is the branch which covers economic modelling and is the area with which we wish to engage. Economic modelling can be further split into microeconomics which searches for 'bottom up' descriptions of phenomena, while macroeconomics addresses the economy as a whole by 'top down' reasoning. Microeconomic principles that are widely used in macroeconomic modelling, such as rational agents and perfect markets, have attracted wide criticism because, taken individually, they are contradicted by experiment and experience [7, 8, 9, 10]. Nevertheless, the philosophy of this approach, which seeks general principles to explain wide ranges of phenomena, sits more comfortably with modelling in natural science than much of social science.

We will argue here that social and economic natural laws remain to be discovered. These are likely to be statistical rather than deterministic, but this is no novelty in science as we know from disciplines such as statistical mechanics or quantum mechanics. In fact, we argue more strongly that the extension of natural sciences into the previously unexplored areas of complex systems and nonlinear dynamics, which modern computing power has made possible, provides signposts for similar developments in social and economic science. Quantitative modelling of the human–Earth System can be a catalyst for such development. This is an unashamedly positivist agenda which is intended to complement, or at least parallel, more traditional constructivist[2] approaches of social science.

2 Constructivism is a theory of knowledge that argues that humans generate knowledge and meaning from an interaction between their experiences and their ideas. Perhaps its most extreme modern manifestation is in the postmodernism expounded by philosophers like Foucault and Derrida, which can be paraphrased (crudely) as the view that all knowledge is socially constructed and hence subjective.

Many unconnected lines of current investigation are relevant to this goal. To bring them together we will organise them around some of the most important characteristics of the development of natural science over the last 400 years. These include:

- integrative questions of sufficient practical importance or intellectual curiosity that they focus the attention of the best thinkers
- observed regularities that speak of underlying laws
- the co-opting or inspiring of mathematical techniques
- data collection
- testing of hypotheses against data.

We will spend most time on the first two of these points, concentrating on the type and range of models that it is possible to construct. We will pass more quickly over the technical approaches they will require; this is a topic for a companion paper. We will then sketch out the current state of the art as we see it and, finally, the most important gaps that need to be filled as we set out to address the fundamental question addressed by the Australia 2050 Program.

It seems apposite to end this introduction by asking why the second word in our title was 'modelling' rather than 'prediction' or 'understanding'. Joshua Epstein, in his illuminating essay 'Why model'[11], gives 16 reasons for modelling other than prediction, which many people assume is the only goal of modelling. Among the most important of those other reasons are:explaining, illuminating core dynamics, guiding data collection, discovering new questions and placing bounds on plausible outcomes. More fundamentally, Epstein points out that modelling is universal; it is just that most people's models are implicit and unconscious. Boschetti et al. [12, 13], in this volume, develop this view to a more radical conclusion. They argue that modelling is what living things do. In other words, all living things continually construct predictions (models) of the consequences of their interaction with the physical world and then respond to these predictions. These 'models' may be wired by evolution into the nervous systems of lower animals, or in the case of humans, may be heuristics honed by evolution and encoded in our genomes. The kind of models that we are discussing here are vastly different in degree but not in kind from such simple instinctual models and they serve the same purpose. They allow us to form a view of where we are going as a group, a population or a species, and to take avoiding action if it is a place we don't wish to end up. A critical difference is that we are now a species with strong global connections, so that evolved heuristics are no useful guide to sensible behaviour. We are taking the view in this paper that the scientific method is the best means we have for constructing predictions of the likely consequences of our actions as a connected species in the 21st century.

2 Integrative questions

The history of science and mathematics since The Enlightenment is replete with major questions and challenges that were embraced by the research community. Some of these were commercial. Before Galileo trained his improved telescope on the heavens, it was providing early warning of ships approaching Venice and giving an edge to his sponsors in the Venetian market. Indeed, the age of exploration and the need for precise navigation was a spur to astronomy through the 16th, 17th and 18th centuries. Some questions were primarily intellectual: the interpretation of the fossil record spurred the invention of geology; classification of the natural world led to Darwin and Wallace's Theory of Evolution. And some were primarily humanitarian, as when confronting the scourge of infectious disease led to the development of microbiology. Understanding radioactivity and nuclear physics engaged much of the scientific world in the early 20th century, while the second half of the same century saw the flowering of genetics and cell biology. Most recently, the problems and challenges of climate change have catalysed a huge growth in our understanding of Earth System dynamics, so that it is probable that the decades around the turn of the 20th century will eventually be seen as the era of Earth System science.

These problems and questions were global in nature and engaged the best scientific minds of their age. On a more modest scale, what questions can we pose to galvanise the growth of a quantitative science of human–Earth System dynamics? Here we propose three—two of them broad and one more specific.

Question 1: How do we dynamically couple the physical planetary boundaries of Rockström et al.[14] by including the influence of human actions on planetary systems?

The planetary boundaries concept [14] has proved to be a powerful framing of the physical consequences of global change. This approach takes the dynamical state of the planet through the late Holocene, the period in which all human civilisation developed as a desirable state and which we do not wish to leave inadvertently. It then defines nine threshold levels for physical attributes of the Earth System that we should not transgress if we want to avoid crossing 'tipping points' from which recovery would be painful or impossible[3]. The logic of the planetary boundaries approach assumes that we have a reasonable understanding of the dynamics governing the crucial biogeochemical processes for which thresholds can be clearly identified[4].

3 The boundaries are specified values of: climate change, ocean acidification, stratospheric ozone depletion, N and P cycles, freshwater use, land use change, biodiversity loss, atmospheric aerosol load, chemical pollution.

4 Subject to assumed future refinement and modification of course.

It is immediately obvious that several of the nine ‘state variables’—specified values of which form the boundaries—are strongly coupled by the underlying dynamics of the natural Earth System (Figure 1a).

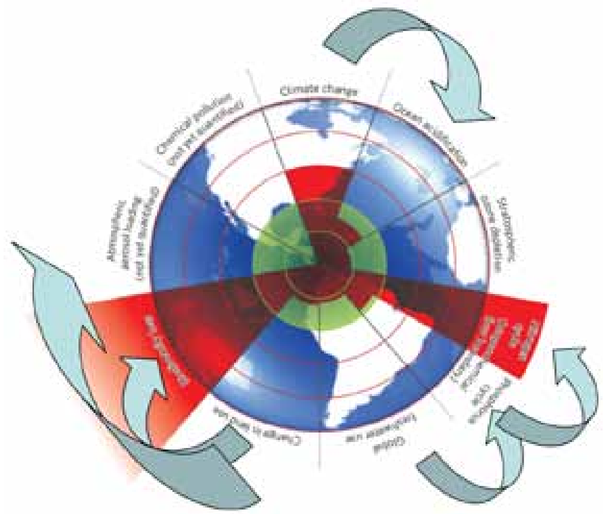

Figure 1a: The natural dynamics of the planet couple groups of boundaries.

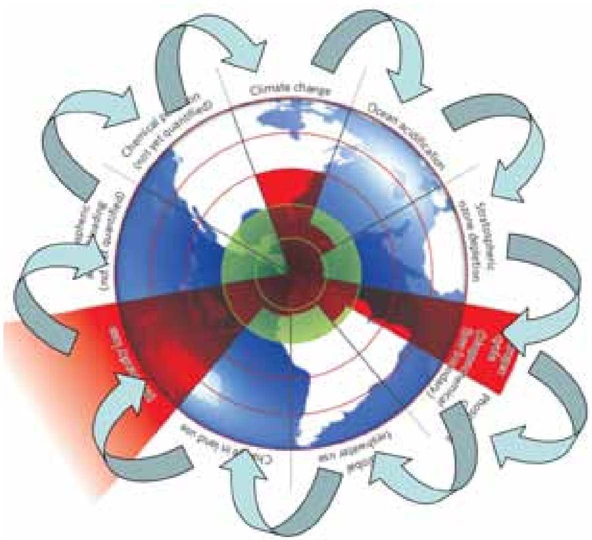

Figure 1b: Food production, urbanisation and economic growth driven by population growth ´and human aspiration dynamically couple all the boundaries. Figures 1a and 1b are adapted from Rockström et al. (2009) [14].

For example, the nitrogen and phosphorus cycles are coupled to the hydrological cycle (freshwater use) and also to the carbon cycle (climate change). However, all of the nine indicators are coupled if we extend planetary dynamics from the natural Earth System to the human–Earth System. Climate change and ocean acidification are consequences of human interference with the carbon cycle, one driver of which is land-use change, but land-use change has also led to rapid loss of biodiversity and is accompanied by increased diversion of fresh water to human use (Figure 1b).

Ultimately, these changes are driven by population growth and the increase in economic activity that has led a significant fraction of the world out of the Malthusian trap [15, 16]. This economic activity depends on fossil energy use, which in turn is causing ocean acidification and climate change.

A first step in answering Question 1 would be to include the physical flows of energy and materials that are mediated by human actions in the same framework as the natural biogeochemical cycles. This is the province of economics and, in particular, of macroeconomic modelling, in which physical quantities are tracked. In effect, such models are calculating the social and industrial stoichiometry of the planet.

Current macroeconomic models make simple assumptions about the microeconomic factors that drive the flows of material and energy that accompany economic activity. These drivers implicitly include the aspirations, choices and mental models of producers and consumers and those government actions that affect markets. Generally, these models also assume some critical factors affecting productivity and economic growth such as the rate and causes of innovation. Improving the realism of these elements of economic models takes us into the realm of social science, as we must now consider the interplay between individual actions and societal constraints as it affects demographics, aspirations at population level, the role of information, the contagion of ideas and other factors. Although this question is posed at a global level, it applies with equal force to the question of defining a 'safe operating space' for Australia in the 21st century.

Our first integrating question was posed from the standpoint of physical processes. Addressing it at successively deeper levels has brought us into the realm of social science and social dynamics, and this prompts a second integrating question that is both more ambitious and more difficult than the first:

Question 2: Can we expand the concept of planetary boundaries to the human–Earth System so that we identify threshold values of coupled biophysical–societal parameters that must not be transgressed if we wish to avoid disastrous tipping points?

Question 2 implies that there are social analogues of the Holocene that we do not wish to leave inadvertently. We can make this concrete by positing that this desirable state is defined by minimal conditions of access to life's necessities, together with universal human rights such as social equity, gender equality, education, and self-determination define [17]. In a recent Oxfam discussion paper, Raworth (2012) [18] juxtaposed these social desiderata with the biophysical parameters of Rockström et al. [14] to define the biophysical–social safe operating space as a doughnut, or torus bounded on the outside by the biophysical parameters and on the inside by the social–ecological ones. It is clear that the boundaries are coupled. For instance, access to potable water depends on the total freshwater available, while freedom from hunger requires that sufficient food be produced. Nevertheless, the kind of dynamics that we need to understand when we consider how the thresholds that bound this torus are coupled, are more complicated than simple arithmetic. We can illustrate this by an example: that of the links between inescapable volatility in food availability and price, inequality in wealth and social unrest.

Roughly one-seventh of the world's people suffer food insecurity. The primary cause of this is the 'distribution gap'—although enough food is being produced in the world today to feed everyone, the calories fail to reach roughly 1 billion hungry mouths because of inadequacies in food trade and distribution and the insufficient purchasing power of the poorest [19]. While most food is still produced close to where it is consumed, a significant and growing fraction of the world's food is traded internationally. Production of food in modern agricultural systems is very dependent on energy for fertiliser production, farm operations, transport and processing. Oil and gas, which supply much of this energy, are also internationally traded between a few producers and many importing countries. World trade in food and energy, and the monetary system that enables it through markets and credit, form extremely complicated networks. Analysis of these networks [20, 21, 22] reveals that they have forms that are conducive to both dynamic [23] and topological instability. Dynamic instability means that even small shocks to food and energy availability can propagate through the network, growing in amplitude as they do. Topological instability means that flows are vulnerable to the failure of critical links or nodes. Together, these features mean that the supply of food and energy is intrinsically volatile even without the major shocks caused by events such as subprime mortgage failures.

For example, the Food and Agriculture Organization food price index rose by over 50% in 2008 following growth in oil prices, then fell in 2009–10 before hitting new heights in 2011–12 [24]. After almost two decades of steady prices to 2007 we are now seeing unprecedented price volatility superimposed on a trend of price increases. It remains to be seen whether this will continue, but the structure of the underlying trade and supply networks suggest that this kind of behaviour should not be surprising.

Wealth is unevenly distributed within and between countries in the world. This is illustrated in two ways in Figure 2.

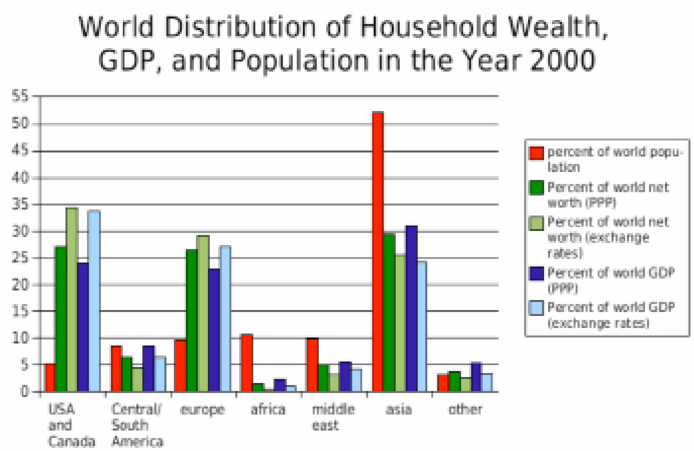

Figure 2a: Variation of share of global population and wealth for major geopolitical groupings. From, Davies et al.

Figure 2a shows the relationship between world population share and share of global wealth for major geopolitical groupings. It is very clear that the world today is divided roughly into 15% of the population who are 'haves' and the 85% who are 'have nots' A different way of displaying this global between-country inequality is Figure 2b, which plots cumulative population against cumulative wealth as a Lorenz curve [25]. Perfect equality is denoted by the 1:1 reference line. It is widely assumed that we are observing a trend towards global convergence of income and wealth led by major developing or emerging economies like China's or Brazil's [26]. However, both evidence and opinion on this is mixed [27, 28, 29]. Even assuming convergence, it will take many decades before the lead of Western nations, which were the first to industrialise, is lost. It is obvious that the poorest countries will be those least able to cope with rapid increases in food and fuel prices without significant hardship.

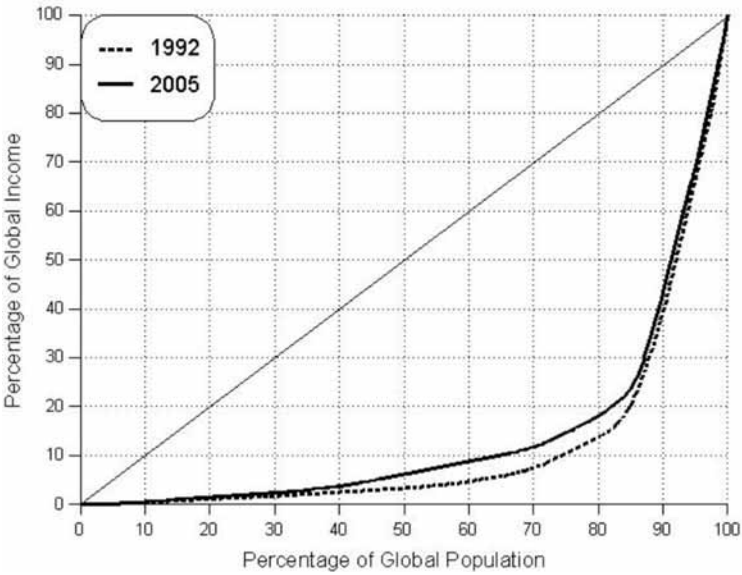

Figure 2b: Lorenz curve illustrating wealth (GNP/capita) inequality between N countries. Data source: United Nations Development Program (2007) [30]. From Marshall and Goldstone (2007) [25].

Gross national wealth or income is, however, only part of the story. Income inequality within countries can mean that even polities whose national GDP is not too small may see a rapid increase in the number of their citizens who are food or energy insecure as prices rise. We can construct Lorenz curves for individual countries, but it is more convenient to summarise the inequality in a single number, the Gini coefficient [30]. A low Gini coefficient indicates more equal income or wealth distribution, while a high Gini coefficient denotes more inequality. Worldwide, Gini coefficients range from approximately 0.23 in Denmark to 0.71 in Namibia. National Gini coefficients are widely scattered, with no strong correlation with GDP. Some rich developed countries have relatively high Gini coefficients, while some poorer countries are quite egalitarian. Nevertheless as Figure 2c shows, Gini coefficients greater than 0.5 are only found in countries with GDP per capita below U$10 000 (2001 equivalent). When rapid rises in food prices impact countries with both high Gini coefficients and low national GDP the food distribution gap can widen alarmingly quickly, so that a significant fraction of the populace cannot access or buy food in adequate quantities. For example, in Sierra Leone, a poor country with a high Gini coefficient of 0.62, the price of food in 2008 rose 300% in 6 months [31].

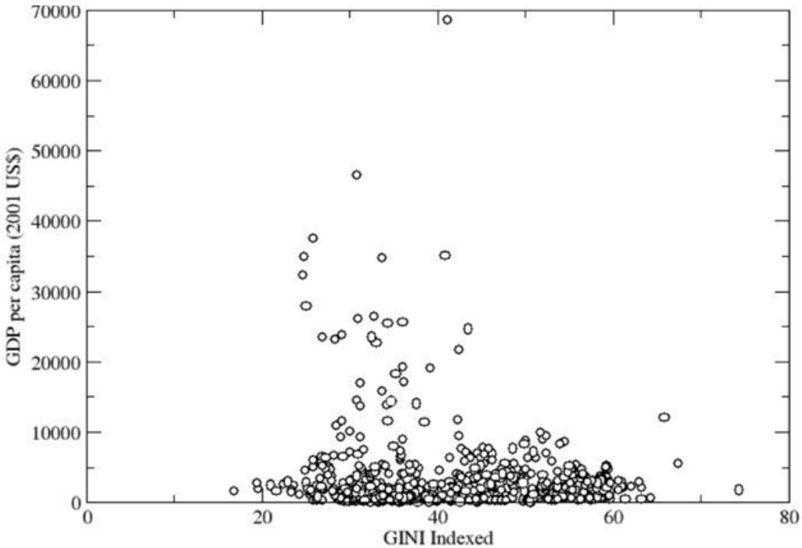

Figure 2c: Gini coefficient expressed as a percentage vs. GDP/capita for N counties. Source: World Bank. Data is from 2004, the latest year for which GDP and Gini coefficient values are available for a representative range of countries.

There has been a good deal of recent analysis of the relationship between food (and energy) insecurity and social unrest, rebellion, conflict and war [32–35]. A comprehensive Index of State Fragility was constructed by Marshall and Goldstone (2007) [25] and tracked since then [36]. This index integrates many of the factors that lead to state failure and move a society out of a social safe operating space. State failure is evidently a human-biophysical tipping point. Its dynamics involve the intrinsic volatility of intersecting food, energy and financial markets, the poverty, inequality and consequent vulnerability to food and energy insecurity of a society and the social and institutional settings that modulate the reaction of the people to these circumstances.

A clear difference between this kind of tipping point and the purely biophysical ones of Rockström et al. (2009) [14] is that the social safe operating space is itself a normative concept with considerable geographic, ethnic, historical and, most contentiously, ethical variability. Hence answering Question 2 has two major components. The first involves defining desirable or acceptable social states, and the second requires the coupling of social processes and the relevant human–Earth System dynamics that determine whether societies can remain in these states over the long term.

A version of this question, downscaled to Australia, is implicit in the concept of a safe operating space for the human–Earth or 'social–ecological' system that is Australia in the 21st century. One possible focus of such a national version would be the conflict that could arise when we plan to increase urban density to improve transport and energy efficiency and minimise costs in reticulating water and waste, but ignore changes in social interaction, social stratification and societal cohesion that result from the rapid decreases in personal living space, especially for poorer groups, that these strategies imply

Question 3. Are the United Nations Development Programme's Millennium Development Goals[5] simultaneously achievable without transgressing the physical planetary boundaries?

Our first two motivating questions are broad in scope. The third is more focused, specific and topical: are the United Nations Millennium Development Goals (MDGs) fundamentally self-defeating? It has been persuasively argued that the poorest countries in the world are still operating in a Malthusian economy [15]. The first characteristic of such an economy is that any innovation that increases per capita wealth leads to increased fertility and decreased mortality, and so to a population increase (and vice versa). Second, the growth in national wealth is much slower than population growth, so that the increased population reduces per capita wealth and the 'subsistence level', where births equal deaths, is inexorably driven towards greater poverty. If we accept that many of the countries targeted by the MDGs are operating in the Malthusian mode, then three of the MDGs—reducing child mortality, improving maternal health and combating HIV/AIDS, malaria and other diseases—which, taken together, all act to increase population, have the potential to confound the first goal of eradicating extreme poverty and hunger. Unless richer nations take action to ensure wealth grows faster than population and is equitably spread in such countries, these four MDGs are in opposition. A full integrated analysis of this possibly self-defeating enterprise would provide a high-profile integrating question for human–Earth System dynamics to address. The answers have obvious relevance for Australia as a developed and rich nation in close proximity to major foci of poverty and population growth in the Asia–Pacific region.

5 The UNDP's Millennium Development Goals are to:

- Eradicate extreme poverty and hunger
- Achieve universal primary education
- Reduce child mortality
- Improve maternal health
- Combat HIV/AIDS, malaria and other diseases
- Ensure environmental sustainability
- Promote gender equality and empower women
- A global development partnership.

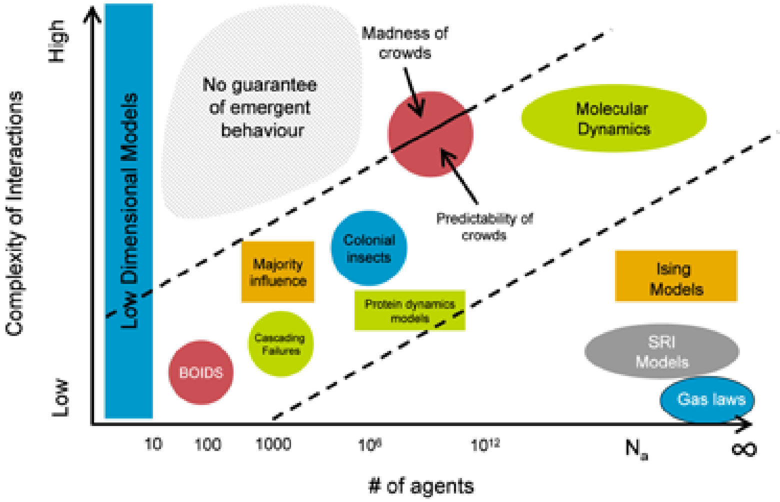

Figure 3: This diagram illustrates schematically the concept that there is a trade-off between the number of agents interacting in a system and the complexity of their interactions so that 'stable' emergent behaviour requires more agents if their interactions are more complex. The region between the diagonal lines is the domain explored by complex systems science.

3 Observing regularities that speak of underlying laws

An objection that is often raised to the idea of integrating social dynamics with natural dynamics is that the unavoidable dependence on contingency in a system where humans are actors places such limits on the capacity for quantitative description that prediction, even in a probabilistic sense, is doomed to failure. A related objection is that the act of prediction in itself will influence the future trajectory of human affairs, rendering any predictions false. And a third objection is that we possess no quantitative theory governing the social dynamics that lie at the heart of human–Earth System dynamics. Indeed, at this point we usually encounter epistemological disagreements with the main body of social scientists [6, 8, 37].

Against this third objection we set recent developments in complex systems science, especially as translated into models of the physical economy, but also including social network theory, evolutionary game theory and similar fields (§4 below).

In reply to the first two objections, we hypothesise that, at sufficiently large scale, modelling, the human–Earth System is no different in kind from modelling other complex systems such as the climate. Even though the climate's sensitivity to initial conditions ensures that just one of an infinite number of world lines will be followed and that this chosen trajectory will be path-dependent, we nevertheless believe that we can model climate change successfully. The paradox is resolved by the existence of an attractor for climate that evolves much more slowly than the chaotic secular motions we call weather or climate variability. If we expect the human–Earth System to behave in an analogous way, it must also contain attractors at appropriate scales. Their existence would imply that the strong influence of human foresight and intentionality, which allows contingency to dominate, applies primarily to small subgroups of society. In contrast, on population or global scale there are societal attractors that evolve slowly relative to the space and time scales over which societal characteristics such as received opinions, norms and public choices change. Individual worldlines on these attractors are sensitive to perturbations by individual or small group behaviour, but general societal behaviour is confined to the surface of the attractor.

So is there clear evidence of regular repeated patterns of behaviour that suggest underlying and universal principles of societal organisation that modelling can capture?

Attractors in the human–Earth System

Let us extend the climate metaphor by defining the concepts of societal weather and societal climate. Societal weather refers to those social dynamics that are so dominated by the contingency of individual or small-group actions that they are effectively unpredictable. Societal climate comprises repeated or enduring (but not necessarily periodic) patterns of behaviour. Intuitively, we can think of such regularities as having dominant time scales that are significant relative to a human lifetime, (e.g. a generation or longer) or that involve so many people that individual behaviours are insignificant compared to the emergent actions of the masses. A tentative and incomplete list of examples of societal climate, starting from the largest scales of space and time and moving to smaller might be:

- the Neolithic Revolution—the transformation from hunting and gathering to agriculture and pastoralism
- the Industrial Revolution
- the demographic transition
- large-scale changes in social attitudes such as
    - the Axial Age
    - the Enlightenment

- the welfare state (extension of altruism to non-family members)
    - female emancipation
    - the outlawing of slavery in the West
    - political movements
- rise and collapse of hegemonies
- transitions in social organisation (e.g. chiefdoms, heroic societies, feudalism, city-states, nation-states)
- urbanisation growth and decay of cities
- overexploitation of finite resources.

The first three examples above might be thought of as societal 'ice ages', given their transformative nature. Each led to massive increases in both social complexity and population [38, 15. The increased complexity could not be unravelled without population collapse. In contrast, the continual rise and collapse of empires or hegemonies [39, 40] might be viewed as examples of 'societal ENSOs', in reference to the El Nino–Southern Oscillation climate pattern.

The ubiquity of these processes is a strong indication that they are fundamental features of human society interacting with its environment. Agriculture was invented independently on at least six sites widely separated in space and time, while urbanisation and the cycling of hegemonies appears to have followed parallel patterns in the Old World and the Americas, despite the separation of their human populations in the Palaeolithic [41, 41]

If we accept that societal climate and the underlying societal attractors exist in the sense set out above, it is reasonable to ask why this should be so. We suggest three reasons:

- First, that the constraints imposed by physical planetary boundaries (at any stage of technological development) are sufficiently strong to keep important features of the human–Earth System within predictable bounds.
- Second, that consistency between interacting sets of societal choices imposes further strong constraints on societal developments: path dependency means that prior choices can exclude many later opportunities.
- And third, that fundamental features of human behaviour result from evolved human nature and lead to repeatable patterns of societal dynamics, with the implied assumption that such dynamics are amenable to modelling by appropriate methods.

These patterns of social dynamics will be manifest in different societal properties such as population, resource use, physical infrastructure or social complexity. Not all of the list of possible societal climate attractors suggested above will be seen in all of these variables. For example, the procession of hegemonies seen in history prior to the Industrial Revolution involved growth and decay in social complexity, urbanisation and social organisation, but occurred against a background of imperceptible change in innovation, resource use, general standard of living and population [15].

We propose finally that these fundamental features of societal dynamics are amenable to quantitative modelling, especially material, energy and information flows, broad measures of social complexity and technological innovation rates, if we use the appropriate mathematical tools.

4 Mathematical techniques for modelling the human–Earth System

Natural science grew in step with applied mathematics. Science variously stimulated the development of mathematics, as in Newton's calculus, applied contemporary developments in pure maths, as in Einstein's use of Riemannian geometry, or was itself guided along its development path by the mathematical tools available, as in the simultaneous emergence of linear operator theory and quantum mechanics in the early 20th century. So what are the appropriate mathematical techniques for modelling the human–Earth System? In this section we want to briefly discuss three broad approaches we think are essential partners in the modelling enterprise we are proposing.

System dynamics and dynamical systems theory

Most of the current descriptions of human behaviour contained in large-scale models of the human–Earth System employ algebraic, differential or difference equations to model average properties of society. Modern developments in system dynamics offer fundamental understanding of the kind of behaviours we should expect from the human–Earth System. These would include the nature and existence of simple, strange and stochastic attractors, hysteresis and tipping points or catastrophes [43, 44]. Perhaps most fundamentally, these developments warn us that expectations of system behaviour based on experience with quasi-linear, deterministic systems is likely to be actively misleading when we come to the human–Earth System.

Agent-based modelling

The difficulty of representing social dynamics at population scale has been one of the incentives for the development of models of human behaviour at the individual level—so-called agent-based models (ABMs) or multi-agent systems [45, 46, 47]. There are many examples of the successful application of such models at a range of scales. These include models of markets where ABMs yield realistic behaviour in contrast to the efficient markets assumed in most economic models [48], or the description of crowd behaviour [10], or of disease spread [49, 50], where ABMs capture critical features which continuum models usually ignore [51]. More fundamentally, it has been argued that ABMs are the natural framework within which to approach the modelling of complex systems comprising many interacting agents [52].

Network theory

Social interactions take place on a network of human–human contacts. Economic systems comprise interactions between individuals, companies, conglomerates, countries and trading blocs. Network analysis has shown that many of the properties of such systems are determined to a greater or lesser degree by the topology of the contact network, regardless of what actually constitutes the interaction between the elements (or nodes) of the system [53]. When we consider social or economic networks, we find that it is usually much easier to describe the network structure than to catalogue all the possible types of interaction that can take place across the links. If there are some types of important societal or economic behaviour that are then largely determined by the network topology, we can gain important qualitative insight and even quantitative predictive power by analysing the topology. Network theory, especially in combination with evolutionary game theory, has delivered important insights into fundamental features of human behaviour such as altruism, cooperation, the spread of ideas and rapid shifts in social attitudes or norms [54–62], and references therein.

In practice, we will need to rely on all of these approaches in judicious combinations to construct appropriate models, a point we return to in Section 6.

5 Data collection and the testing of hypotheses against data

We began by saying that testing hypotheses against evidence is at the core of the revolution in thinking which led to modern science and built the modern world. It must clearly be an essential part of the program we are proposing. Moreover, as pointed out by Epstein ([11]; §1 above), one purpose of model building is to guide data collection. Our expectation that the human–Earth System will usually exhibit the behaviour of a complex adaptive system warns us that some attempts to understand, validate or calibrate our models may be misguided. For example, since the global financial crisis of 2008, the financial community has spent much effort trying to find deterministic cause-and-effect relationships to explain individual peaks and troughs in financial indicators. This is probably futile. Recent research in complex systems science has demonstrated that in complex networks of dependency, conventional notions of cause and effect are essentially meaningless. Instead, what 'causes' do is perturb systems that have their own endogenous, nonlinear dynamics [63, 64]. A more appropriate goal for the financial community would be to understand the intrinsic instability of world financial markets and the role of that instability in generating volatility [65].

In §3 we identified many dynamic patterns from the history of society. Assembling data from recent history, let alone the distant past, to test quantitative models is a difficult and specialised task. The IHOPE Project of the International Geosphere–Biosphere Programme has taken on precisely this challenge and will be a key partner in this research agenda. Costanza et al. (2007a) [66] discuss the data requirements and the goals of IHOPE in detail as well as touching on the question of how much we can learn about the future by studying the past. Here we must confront the question posed by Haldane in 1932: 'Is the history of the last 6000 years in the process of being replaced by a new historical process which will not obey any 'laws' we can detect in the old history'? [5]. Certainly global society is now connected in terms of material and information flows to a degree that it never has been before [21, 67]. It is indeed possible that the social dynamics of humanity have now reached a no-analogue state, so that complete models of the modern human–Earth System can only be compared with history submodel by submodel.

However, this proposition in itself is amenable to investigation. We propose that modelling using the tools we have already discussed is the best way of attempting an answer. Even if some key aspects of the dynamics of the modern world cannot be observed in the past record, there are other historical events that are clearly directly relevant to our immediate future and for which we currently have no convincing or uncontested explanations—for example, the Industrial Revolution, the demographic transition or the great post-1950 acceleration of global development [15, 68].

6 The state of the art in modelling the human–Earth System and the gaps to be filled.

Modelling at two scales—the global and the regional—currently captures most of the effort devoted to quantitatively linking social, economic and natural processes. Global integrated assessment models IAMs) play a key role in Intergovernmental Panel on Climate Change assessments of climate change [69, 70]. (These models are used to calculate emissions of greenhouse gases caused by human activity as an input to physical climate models and also to compute the impact of the resulting climate change on economy and society. Typically they contain economic and demographic modules as well as descriptions of physical processes such as agricultural production, energy generation and climate (see [71] for a general description of models of this class).

The economic modules of IAMs parameterise human behaviour implicitly through the assumptions of neoclassical economics, including efficient markets and representative human agents who operate to maximise their profit and consumption. Experimental economics and psychological studies tell us unequivocally that humans individually do not behave in this way, while the question of whether markets are actually efficient in the long run remains contested in economics [7, 9, 10]. The models also explicitly assume simple parameterisations of other social factors (or fix them exogenously). An example of this is the rate of technological innovation, a process whose drivers and constraints are poorly understood and for which there exists little or no consensus on mechanisms, or even on evidence. Most fundamentally, their simple equilibrium economic formulations essentially forbid the appearance of strongly nonlinear dynamics, making these models incapable of endogenously generating the kind of nonlinear tipping point behaviours we observe in the real world.

The failure of classical economics to predict or offer remedies for the global financial crisis of 2008 lends weight to the views of those within the profession who insist that economic modelling needs paradigm shifts to attain the predictive status of natural science. A comprehensive review of the problems of models based on neoclassical economics, together with some suggestions for the research that is needed, can be found in Helbing and Balietti 2011 [10] or in a host of web-based discussions, e.g. http://www.unifr.ch/econophysics/editorial/show/id/52.

Regional IAMs often contain much-more sophisticated models of human behaviour, usually via the route of agent-based modelling (see §4 above). The most effective models represent dynamics operating at many scales, choosing the appropriate scale and parameterisation for a particular process through a judicious mix of ABM and dynamical systems approaches (see §4 above). Such models represent the state of the art for regional IAMs. A fundamental difference between global and regional IAMs is that the former are usually used to generate scenarios by running the models forward with some set of parameter choices. Regional models, in contrast, are often used in participative mode, where the model is primarily used as a tool for engagement with communities or managers. The model is then used to demonstrate the physical or economic consequences of human choices [Boschetti et al. 2011, this volume, Chapter 8].

The use of these models in this participative mode is also a practical recognition of the fact that our ability to model many aspects of human behaviour a priori is severely limited. Instead of supposing that the model can capture contingent social behaviour, human 'liveware' is cooped in both developing the model structure and eliciting the human responses and patterns of interaction that the model requires. This can be a positive feature. Used in this way, the model reproduces the biophysical processes that would result from the choices and actions of the participants in the model development. The participative approach is now widely applied and has reached a high level of sophistication [72].

A key message we take from this supports the hypotheses in §3. At small group size in any single realisation, contingency can rule. At this scale, processes that confound predictability dominate, such as the response of the human agents in the model to the model's predictions. Contrasting the dominant role of contingency at regional or small-group scale (say up to a few hundred people interacting in a social setting) with the observed regularities of the human–Earth System at large scale, which we noted in §3, raises the question we flagged earlier: at what scale (if ever) does strong dependence on contingency weaken or even disappear? This is a critical question that determines the scope of possibilities for modelling the human–Earth System at global scale.

In Figure 3 we schematically plot observed regularities or emergent behaviours of systems [73] against two variables: the number of agents and the complexity of the interactions between them. The obvious deduction is that in many circumstances, if enough agents are interacting, then 'predictable' properties of the system will emerge. What we do not have at the moment are robust theories of whether and where agent numbers cancel out complex agent–agent interaction and switch contingent and effectively random behaviour into behaviour with some useful degree of predictability.

What is clear is that there is a significant gap in scale and approach between global IAMs, whose size, complexity and recourse to equilibrium formulations makes them ill-suited to investigating strongly nonlinear dynamics, and regional IAMs whose social dynamics tend to be ruled by contingency. This suggests the need for another level of quantitative modelling, which we could call IAM's of intermediate complexity, or IAMICs. These would allow us to explore the consequences of parameterisations of social dynamics coupled with the biophysical world, in which the full range of system behaviour could be explored. There are some examples of very simple precursors to such IAMICs, such as Grigg et al. (2010) [74] and Brede and deVries (2010) [57], but the development of IAMICs that truly represent nonlinear world dynamics would be, we believe, a powerful organising focus for the program we propose.

7 Concluding remarks

Is quantitative modelling of the human–Earth System a new science? Modelling societal dynamics is certainly not a new idea. Historians and sociologists have been proposing qualitative models of societal change for a century. In his far reaching book, *Deep futures*, Cocks (2003) [5] devotes a chapter to this subject, comprehensively surveying the contributions of social scientists and historians, starting with the seminal works of Marx, Weber, Durkheim and Spengler. Cocks contrasts these views with attempts to understand the mechanics of societal change derived from analogies with ecology and biological evolution. While all these theories can be falsified in principle by new information, they are overwhelmingly subjective and have rarely been subjected to the test of translation into quantitative mathematical models.

Here we have made the strong claim that developments in complex systems science have opened new windows into the description of societal dynamics and new ways to fuse this with the dynamics of the natural world. The inexorable rise of computational power continues to widen the space within which these new developments can play. In our view, these developments have changed the rules of the game, so that the time is now ripe for real advances in integrative modelling of the human–Earth System.

It is tempting to close with another meteorological analogy. The idea of modelling the weather numerically was proposed and attempted by LF Richardson in 1910, long before digital computers existed. In the 1950s, John von Neumann saw weather modelling as one of the strongest motivations for building digital computers, and indeed this was one of the first tasks they were given. Despite this, it is only in the past two decades that weather models consistently outperform ‘persistence’—that is, the prediction that tomorrow’s weather will be roughly the same as today’s. We may have finally reached this point in modelling social dynamics.

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