6

Looking Forward to the Future

Introduction

In order to strive toward sustainability, though we can profit from studying the past and the processes that led to the present, we also need to develop tools to look into the future itself. That poses another, very different, set of challenges.

As I argued in Chapter 3, the emergence of modern academic science and scholarship was, and still is, based upon the idea that one must be able to corroborate any hypothesis, demonstrating the correctness of any observation. This has heavily biased our scientific perspective toward the relationship between present and past, explaining present phenomena by offering a perspective on the past that could be interpreted as leading to present-day observations. Such a perspective could be informed by documents (in the widest sense) pertaining to that past, such as archaeological artifacts, historical texts, fossils of extinct animal species, etc. But of course that does not help us to elaborate a relationship between the present and the future. Nothing can be documented about the future, so from a scientific career perspective looking at the future is not very rewarding.

As stated in Chapter 1, it is one of the tenets of this book that thinking about the future must indeed be developed into a coherent approach, even though we may at present not quite see what that approach will look like. After all, it took western science four centuries to develop current scientific approaches to relate the present to the past and the past to the present. At the beginning of that process scientists were casting around without much sense of where their ideas might lead, just as is the case for scientists today who are looking at the future. There is therefore in my opinion no reason why we cannot develop approaches to thinking more systematically and coherently about the future. Moreover, in the last century and a half or so, many of the natural sciences have developed theories and models about processes of many kinds that are so accurate that they allow the (generally short-term) prediction of future behavior of a range of systems. A recent, but for many people rather abstract, example is the proof of the existence of gravitational waves. But there are many such examples: based on our knowledge of physics and mechanics, engineers can closely anticipate the performance of an engine, the solidity of a bridge, the destructive power of a nuclear bomb. Astronomers can predict the current and future position and many characteristics of planets and stars. Medicine can predict the efficiency of a new vaccine, the probable course of all kinds of epidemics, and the evolution of many illnesses. In all these cases, such predictions are based on (near) complete understanding of the dynamics involved.

Some of the predictive power of science applies to the very long term (billions of years), such as in astrophysics. But it can also apply to the very short term (microseconds) such as in the case of the complex processes leading to a successful hydrogen bomb explosion, or even ultra-short term (sub femtosecond) interactions such as in photon–matter interaction. Whether such predictions are dependable is related to the complexity of the phenomena concerned. Prediction is much less effective for complex systems such as phase transitions, self-organization (the emergence of snowflakes can be predicted, but not their structure), and the kind of physics treated in Chapter 7. Even in a limited domain such as the economy, scientific prediction is often more fantasy than reality because it is based on dynamic equilibrium models that assume that the current situation may change, but if it does, it will do so only incrementally.

The highly complex issues related to human individuals, societies and their environments generally involve many more dimensions and parameters than those I have just mentioned, so that explanations, let alone predictions, in these domains are very much more difficult. Yet, in view of the acceleration the world is currently going through, we can no longer delay the development of a deliberate strategy to learn from the past about the present and for the future in terms of socioenvironmental matters and the dynamics playing out in societies (Dearing et al. 2010; van der Leeuw et al. 2011; Costanza et al. 2012; van der Leeuw 2014). This being the case, how do we go about it?

Past Perspectives on the Future

When in our quest for understanding we have looked at the past to gain insights about the future, we have rarely used the resultant knowledge to its best advantage. We have derived different (often discipline-dependent) chains of cause and effect, which have been (more or less linearly) extrapolated via the present into the future. The future has thus been negotiated via uncertain and partial extrapolations from different visions of the past and the present, and this is clearly suboptimal. For one, this approach does not open the door to alternative historical trajectories. More importantly, it does not help us understand our relationship with the future. It views the past and the future as "foreign lands" (see Hartley 1953), rather than as projections in different (temporal) directions from the present – the point at which we have the ability to modify the social-ecological evolutionary process according to our ideas.

One conclusion from this state of affairs is that the perspective we develop should be a holistic one – we should not fall back into the trap of separating challenges and research topics into separate disciplines. Designing such a holistic approach requires that we find ways to simultaneously observe patterns in many dimensions, a kind of observation for which traditional Western science is not very well equipped. One way to illustrate this is by reference to the difficulty of solving the Rubik's cube. One cannot get the cube "in order" (so that each side has one homogeneous color) by dealing first with one side, then the next, and so forth. The only way to arrive at order is by looking at the patterns on all sides simultaneously and not favoring any particular side at any time.

Analogue and Evolutionary Approaches to Understanding Past and Future

In a paper coauthored with Dearing and others (Dearing et al. 2010), we distinguish two different ways of relating the past to the present: an analogue and an evolutionary approach. The former is the one we have traditionally used to relate past and present (Meyer et al. 1998; Costanza et al. 2007). We compare the past and the present as different case studies and search for differences and similarities that might help us to better understand the present – how it came about, how it functioned, where observations about the past may serve as lessons for our own situation, and what we might do about undesirable aspects of that situation.

In a paper (van der Leeuw 2014) based on a study by Aschan-Leygonie (van der Leeuw & Aschan-Leygonie 2005), for example, I briefly compare two economic crises in the southern French "Comtat Venaissin" region, in the 1860s and in the 1960s, and ask why the first crisis was quickly resolved and the second was not. This leads us to understand that the seeds for the first solution had already been sown before the crisis emerged, and that the crisis was immediately seen as urgent and threatening, so that coherent action was undertaken. The second crisis developed much more slowly, was not seen as urgent, and forced the region to adapt to a situation that was totally new, so that it could not draw upon preexisting marginal solutions as it had in the first crisis. As a result, the second crisis dragged on and had lasting economic consequences.

Though such analogues offer insights into differences and similarities between cases and sensitize the expert, past examples are by definition imperfect matches with the present, especially in view of the very rapid changes the Earth system (including many societies) has undergone over the last century or so (Wescoat 1991; Meyer et al. 1998). As a result, many (but not all) such comparisons between past and present have engendered "just so" stories that alert their audience to potential dangers, often by overemphasizing similarities and underplaying differences between the past and the present.

In my opinion it would be more productive to compare the different cases from a systemic and evolutionary perspective, and to distill from such comparisons an improved general insight in the structure, dynamics, and evolution of the Earth system under different conditions. In such an approach, each case study serves as if it were a past experiment that, if followed in detail over at least some part of its trajectory with an emphasis on the emergence of novelty (novel technology, novel ideas, novel institutions, etc.), would have provided knowledge about the (un) intended outcomes of past dynamic interactions between the components of the system under different conditions. Such knowledge may permit us – once sufficient instances have been studied and their contexts, boundary conditions, structure, etc. have been brought to bear on the actual dynamics observed – to begin to outline models of the interaction of a number of the more general processes to which such systems are subject. A good example is the work of Zhang et al. (2007), who looks at how the accumulation of measures to improve the financial productivity of an economy (for example through streamlining the production chain) ultimately leads to an understanding of the need for fundamental change in the overall organization of labor in that chain. It seems to me that, ultimately, such approaches may enhance systematic assessments of postulated generalized complex system behaviors that can help us develop insights into the future states of these systems (Hibbard et al. 2010).

It is also useful for illustrative purposes to look at evolutionary theory in biology. Although biologists cannot make clear predictions about the emergence of new species, it is possible in genomics to point to probable gene modifications and their impacts, and thus to distinguish probable from improbable futures in the evolution of a species.

Such a systemic evolutionary view of the past focuses on a perspective in which the present remains continuously and strongly connected to the past (Carpenter 2002). But owing to the systemic nature of the perspective, these connections are different from those usually developed by historians because the emphasis is on the dynamic structure of the system studied. They address processes that operate over longer time scales than the example mentioned above; they involve time lags, contingencies, emergent effects, and legacies that are integral to the functioning of the contemporary and future system.

By integrating observational, documentary, and reconstructed data, evolutionary studies could thus provide a developmental perspective on socioenvironmental processes that is critical to understanding all the elements of contemporary system dynamics, including the second order dynamics that are continuously modifying the boundary conditions within which socioenvironmental systems operate. Such long time-series of data and information may be the only way to confirm complex system behavior (e.g., alternative steady states, the adaptive cycle, contingent and emergent properties, and feedback mechanisms) in real-world systems. We can then ask fundamental questions relevant to managing socioecological systems: "Which ecosystem processes or services are apparently stable and resilient?," "Which are trending beneficially upwards?," "Which are on downward trends?," "Which combinations of stresses have led to such current environmental degradation?," "What are the predisturbance properties that could point to targets for environmental restoration?"

Finally, this approach is much better suited to deal with the no-analogue situation that we presently face with respect to the sustainability of humans and their societies on Earth.

Ex Post vs. Ex Ante Perspectives

There are of course fundamentally important epistemological issues with looking into the future. Whereas reductionist science has developed an ex post perspective that examines the origins of phenomena observed in the present, and summarizes those in terms of a limited number of dimensions – often in the form of cause-and-effect narratives or formalizations – that is of course not possible if one wants to develop perspectives on the future. Such perspectives must be developed from an ex ante point of departure, focusing on studying the emergence of novelty (new ideas, techniques, institutions, etc.) that is formulated in terms of possibilities or probabilities.

When I introduce this distinction in my classes, I ask students to think of the first time they fell in love. When that happened, most of them would have been trying to work out how their affair might evolve (developing an ex ante perspective on what was happening), and they would have found an overwhelming, and often contradictory, number of potential futures that confused their feelings. But looking back (from an ex post perspective) on the episode several years later, whether the affair had been successful or not, they would have constructed a very limited number of causal narratives about it.

This also happens to other events and situations, of course. In general, humans think and conceive of many different futures and they conceive of only one or a few pasts. They usually conceive of futures in terms of possibilities and probabilities, risks and uncertainties, involving a relatively high number of dimensions. But they tend to conceive the past in terms that involve a much lower number of dimensions, often only one or two, and construct narratives based on chains of cause and effect. Ex ante they speculate what might happen, but ex post they construct a causal chain about what did happen, describing the origins of where they are at that point.

For the moment, there are no firm ideas about how to assess the relative probabilities of such ex ante future scenarios. But thanks to the work of scientists such as Fontana (2012), we can begin to sketch a roadmap that will bring us closer to our goal. In a paper by Bai et al. (2015) to which I contributed, we propose the outlining of a number of possible trajectories from the present into the future that are compatible with our understanding of the past dynamics that have brought us to the present, and then asking which of these futures is plausible. To determine this, we analyze which among the projected futures would run into internal or external obstacles, inconsistencies, or other challenges, to the point that it would not be realistic to expect them to materialize or persist. In essence, we look at the inherent affordances while trying explicitly to avoid what appears unsustainable, acknowledging that striking this balance is never easy and will always involve both uncertainties and values.

In the next step, we try to decide which of these futures is desirable, limiting the plausible choices further. This should lead to a wider societal and scientific discussion around the question about the kind of future we see for ourselves and our species (see Lévèque & van der Leeuw 2003). In this discussion, the basic values of the society involved need to be made explicit, and linked to the desirable futures selected. Once such a discussion has focused its efforts on a limited set of specific scenarios for its future, we can ask what we need to do to achieve this or that future.

This approach is deliberately solutions-focused but does not aim for immediate solutions that perpetuate the current path dependency, because it is a core thesis of this book that the unintended and unanticipated consequences of every human action and innovation play such an important role that the future is ontologically uncertain. Rather, its goal is to identify potential out-of-the-box ways forward that seem plausible and desirable as well as sustainable over the long term.

Another approach, used for example by Saijo (2017), is to begin by looking at desirable futures by positioning oneself as far as is possible in the future, generating from that perspective a range of desirable futures, then back-casting to the present and designing a roadmap that might achieve the desirable goals by adopting probable trajectories. In this chapter, this is further elaborated in the section on scenario building.

In the end, one may have to develop ways in which these two approaches, forecasting and back-casting, can each be developed in their own right, followed by an episode in which their integration can be negotiated. In doing so, approaches used in engineering, business, and related disciplines would be adopted.

The Role of Modeling

Models (computer- and others) are important novel tools for thought and action (for an easy-to-read general summary of the concept model, see Apostel 1960). They can represent very complex dynamics in ways that allow us to look at them both ex post and ex ante. Such tools are now commonly used in a wide range of disciplines, including the natural, life, environmental, and economic sciences, and in contexts that range from academia to all the major financial and economic institutions (such as governments, central banks, the International Monetary Fund, the Organisation for Economic Co-operation and Development) and the defense establishments of many countries. Outside such institutions, they are known as computer games, and they may involve hundreds of thousands of actors.

Where it is possible to represent evolutionary processes as a set of rules, whether mathematical, numerical, or logical, there is the chance to create simulation models that can be used as management tools. The models used in the Limits to Growth studies (Meadows et al. 1974, 2005) were developed around the idea of a world in which different social and environmental processes are interconnected through flows of energy, materials, and information. By creating a dynamic mathematical model, the authors were able to simulate future patterns of growth and decay in energy demand, resource use, environmental quality, etc. As the sustainability agenda grew stronger, there were increasing numbers of calls for similar modeling tools that can simulate alternative future states of socioecological systems at regional scales, and as a result a whole industry of such modeling emerged.

A key requirement for sustainable management is to be able to gauge the future risk that alternative strategies will transgress major environmental thresholds by looking at thresholds and tipping points, such as for example the minimum density of vegetation cover that protects the ground from runaway soil erosion. Therefore, modeling tools need to be able to operate over at least several decades (but to capture second order dynamics they may need to cover centuries or even millennia, see van der Leeuw 2007), and, importantly, they need to capture the likely big surprises that are inherent in complex systems (Dearing et al. 2006a, b; Nicholson et al. 2009).

Why Model?

We live in a complex world where human actions commonly have unforeseen and unwanted consequences. In the scientific as well as in the political arena two strategies have emerged to cope with this complexity: theory and computer simulation. Theories are ideas about causal relations that are used to inform understanding, choices, and decisions. Given that even the most brilliant theoretician has limited capacities for deductive reasoning, theories are necessarily of limited complexity. Computer simulations are also based on ideas about causal relations, but these are often so complex that only teams of highly trained specialists can put them together. Moreover, not even these specialists can claim to understand all their logical corollaries. Those are the ones that we model in order to understand them.

In a paper published in 2004, I give some reasons for modeling that in my eyes are important. For one, models enable researchers to economically describe a wide range of relationships with a degree of precision usually not attained by the only other tools we have to describe them: natural languages. Because each discipline has its own vocabulary and approach, one of the major difficulties in pluri- or transdisciplinary research is to find modes of expression that are acceptable to all the disciplines involved, and free from the connotations of any or all of them. Models can indeed be used to express phenomena and ideas in ways that can be understood in the same rigorous manner by practitioners of different disciplines, including the natural and social sciences and humanities. An example is the "percolation" model that I use in Chapter 11 to investigate transitions between information processing networks.

Another important advantage of formal models is that the domain of application of formal models is unlimited. It includes all aspects of any discipline. Thus, models may include, for example, kinship, ritual, choice, and behavior, alongside aspects of the dynamics between society and the natural environment upon which it is predicated.

Moreover, I find formal models particularly useful in a multi- or transdisciplinary context because they are sufficiently abstract not to be confounded with reality, and sufficiently detailed, rigorous, and (in the case of some computer models) "realistic" to force people with different backgrounds to focus on the same relational and behavioral issues. Models can therefore dissolve blockages and misunderstandings between disciplines by showing that the match between the phenomena to be predicted after running the model and the actual observed phenomena is close, non-existent, or somewhere in-between.

No less important in a social science context is the fact that formal models are formulated in a different language from the descriptions of the phenomena to be modeled. This has several advantages, of which the most important is possibly that it allows us to abstract in order to highlight features that are in our opinion relevant. It is a common assumption, for example, that one may not compare apples and oranges. Yet if one wishes to explain why oranges are better at rolling in a straight line than apples, one invokes an abstract dimension (roundness) and compares both kinds of fruit in terms of that dimension. The applicability of any particular model to a set of phenomena does not follow naturally from the nature of the phenomena but is defined by the person who applies the model.

Formal models can therefore, at least in theory, be useful in solving problems in which it is important to infer relationships between the observed behavior of certain phenomena and characteristics of these phenomena that remain to be identified.

Moreover, certain kinds of formal models are able to describe the changes occurring in complex sets of relationships with great precision and economy. I will give an example of this in Chapter 14. Owing to these properties, modeling is very suitable for formalizing dynamic theories about certain complex phenomena, which can then be compared with our observations. It facilitates putting flesh and clothes on the bare bones of sequential static data sets by helping them to link dynamic processes to their static outcomes. It should be noted, however, that this implies a somewhat different use and status of the models involved than is common in certain disciplines.

And finally, certain classes of formal models allow us to study how interactions between individual, non-identical entities at a lower level result in patterns at a higher level. This is particularly relevant in the study of many of the collective "hairy" or "wicked" phenomena that are the subject of the social sciences, where the interactions between individuals create the society, which in turn impacts upon the behavior of the individuals or groups concerned. Because of this property, such models are particularly interesting for those of us who study society from a self-organizing perspective.

Support Models and Process Models

Let us now look in more depth at the role of two different kinds of models (van der Leeuw 1998b, 14). In politics, in industry, and in commerce, computer simulations are commonly used as support models: models used to infer the most likely consequences of given actions in some real-world-like dynamic system. Indeed, the computer science and modeling literature often implies that support models are the only rational way of using computer simulations. Computerized models, one learns, are abstract representations of concrete (i.e. real-world) dynamic systems. One will also read that a system is "a set of rules, an arrangement of things, or a group of related things that work toward a common goal" (www.yourdictionary.com/system).

In practice, these models hardly ever hold true over the longer term. In such models, causal relations manifested in the real world are only understood in quantitative terms. We know that poor communications and low food production may limit the growth of an urban center, for example, and can often specify a number of equally plausible mathematical relations that exhibit similar properties. But unfortunately we seldom have theoretical grounds for favoring one of these plausible sets as the definitive model to use.

There are other kinds of models. Process models are used to investigate ideas about a perceived, but imperfectly understood, dynamic system. By analyzing the model in a manner consistent with the perceived mapping between the model and the theory it represents, one searches for logical implications inaccessible by traditional hypothetico-deductive methods. If the underlying structure of the model is quite simple and the range of behaviors it can exhibit is considerable, the study of how the model operates will produce results that are more widely understood than those of support models.

It is equally important to realize that the same set of modeling tools can be used for two very different analytical tasks. Support modelers use computer simulations as test beds for policies, while process modelers build computer simulations as test beds for theories. It is conceivable that one who only ever builds support models could sustain the notion of a system as a group of components with a common purpose or that of a model as an abstract representation of a concrete system. For a process modeler, however, these ideas are manifest nonsense. For him or her, a model is a concrete representation (in the form of equations, marks on paper, switch states in a computer) of an abstract system (a theory).

The distinction between the traditional use of models as abstract maps of concrete systems and the use proposed here of models as concrete maps of abstract systems is not merely a nice rhetorical point. It has profound methodological and ethical implications. On the methodological front, it suggests that the principal function of a model is to evaluate theories and, ultimately, to suggest new theories for future evaluation.

On the ethical front, this distinction forces us to acknowledge that the output of any computer simulation is only as reliable as the theory it represents and the data it uses as input. That does not imply that the use of support models is inherently unethical. We live in a world where current policies must change for the better if humans are to avoid global disaster. Support modeling may be the only means by which complex political, ecological, or sociological theories can be harnessed and put to work. However, if we are to manage our affairs responsibly, we not only need the best support models available, but we also need to accept that the "real world" (whatever that is) may not endorse them.

In most sustainability science, models are common currency. They are used to extend into the future the analytical perspective that has allowed us to understand the socioenvironmental dynamics that have brought us to the present. Procedurally, they are therefore usually inserted at the end of a chain of reasoning, and serve to extrapolate from the present into the future. This leaves the whole construct heavily dependent on the (usually linear) scientific understanding of what drove the past and drives the present.

Challenges to Integrated Modeling of Socioenvironmental Dynamics

In a paper recently published by Verburg et al. (2015), the principal kinds of models that are currently in use are outlined, with some of their characteristics, advantages and challenges (see Table 6.1) as well as some examples of each of these categories. First among these, and relatively rarely touched upon, is the fact that the data brought together in many models have been collected by different disciplines with different schools within each discipline concerned, and often for different purposes. They have been collected with different questions in mind, different disciplinary epistemologies, different methods, and different techniques. This is both a current and a growing problem, as ever-limited research funding forces us to increasingly rely on data collected in the past. We need to develop the practice of systematically extending the metadata commonly included in databases, to include (1) the questions the data were trying to answer, (2) the methods and techniques used in collecting and in analyzing them, (3) the sampling, units of observation, and units of analysis associated with the data, (4) the working hypotheses involved in the research, and (5) the epistemological status of the information derived from the data.

- *Moving beyond conceptual models.* There are many examples of conceptual frameworks devoted to the description of socioecological systems in terms of causal frameworks or systems diagrams that conceptualize the interactions between different system components. Their development is an essential part of any research approach, but one could argue that they are granted too much importance in terms of their role in understanding how a system works, in forming a basis for modeling or even in deciding the sequence of research steps. Conceptualizing the real world is important, but we should remember that more often than not we are simply producing lists of key elements with probable links, and emergence tells us that these may all change through time. Frameworks and conceptual models should be treated as first steps in creating hypotheses that could be tested via a suite of tools and methodologies: they have limited value in their own right because they are the means to an end. This is particularly true in the case of integrated assessment models. Even when they have a generic set-up, they are often not well suited for addressing a specific problem or question and we should avoid defining our research questions by the structure of a (conceptual) model rather than focusing on the societal questions as these are emerging. The tail should not wag the

Table 6.1 Different modeling approaches, with some of their characteristics

Generic model category	*Notable model types*	*Coupling*	*Scales*	*Data and computing*	*Complex dynamics*	*Policy tools*	*Validation and skill*
Deterministic process-based biophysical models	Global climate models; Earth System models	Low potential; social subsystem often represented by plausible pathways and emission scenarios	Mainly global (20–200 km) resolution and long (decadal) timescales	Large data and computing requirements	Theoretically capture feedbacks and emergence in biophysical processes. Lack of feedbacks with other (socioecological) system components	Limited because of high complexity. Scenario results are input in intergovernmental processes	Difficult to validate. Comparisons against historical data and model inter-comparisons are common
Deterministic economic models	General and partial computational equilibrium models	One-way coupling in which biophysical subsystem often reduced to climate effect on the agricultural sector	Regional to global. Often limited spatial detail (world regions); timescales often limited to several decades.	Large data and computing requirements	Feedbacks only accounted for through market mechanisms	Dominant use in ex ante assessment of policy instruments	Difficult to validate. Comparisons against historical data are scarce while model inter-comparisons are common
Reduced-complexity social-ecological models	Integrated Assessment Models. Earth system models of intermediate	Moderate potential but biophysical and social sub-models often	Regional to global scale with decadal to sub-decadal timescales	Somewhat reduced data and computing requirements	Top-down usually lacking feedback or emergence (some EMICs can simulate abrupt	Scenario results are aimed at input into policy processes; models used for ex ante assessments	Limited as above. EMICs tested against paleo-climatic records (e.g., ice cores)

Table 6.1 (*cont.*)

Generic model category	*Notable model types*	*Coupling*	*Scales*	*Data and computing*	*Complex dynamics*	*Policy tools*	*Validation and skill*
	complexity (EMIC). System Dynamics Models	simply coupled in an integrated model environment			changes). Social subsystem often reduced to profit optimization or simple heuristics		
Agent-based social-(ecological) and cellular (social)-ecological models	Agent-based models (ABMs), land-use change models	High potential but not frequently implemented	Generally local to regional scale and relatively short timescales with often annual resolution	Rule based. Strong variation in data and computational needs. Strongly relying on either theory or empirical data	System-level dynamics often emerge as a consequence of low-level interactions and feedbacks	Limited application, but examples of participatory use exist	Either based on ability to reduce pattern and dynamics or particular empirical data. Increasing focus on validation of system behavior
Simple toy socio-ecological models	Conceptual models, games	Highly variable but high potential	Any scale	Mostly low. No use of empirical data	Able to simulate complex dynamics but with oversimplified assumptions	Low potential. Learning tools	Mostly not applicable

Source: Verburg et al. (2015), published under CC-BY-4,0.

dog! Any model building or application should start with a clear rationale for the choice of a particular model approach or system conceptualization based on the questions and hypothesis of interest.

- *Modeling safe operating spaces.* A significant development in recent global environmental change research has been the introduction of the concepts of planetary boundaries and safe operating spaces for humanity (Rockström et al. 2009a, b; Steffen et al. 2014), in order to focus on identifying the critical limits or thresholds for major biophysical variables that steer the climate, biosphere, and hydrological systems that underpin social wellbeing. Modeling safe operating spaces to a level that can inform policy thinking will require information about the desirable and undesirable development pathways for humanity at a range of spatial scales. There is a gap between oversimplified toy models that can simulate complex social-ecological change at global scale (e.g., Motesharrei et al., 2014) and global climate models that can capture complexity but only for the climate system. To inform the discussion on safe operating spaces, there is a need for a new suite of models that moves away from the conventional approach of driving models forward in time in the light of particular scenarios, and instead focuses on stable and unstable social-ecological dynamics associated with alternative development pathways. One recent example of such an approach is the project "The World in 2050" (Sachs et al. 2018).
- *Feedbacks and emergent properties.* Owing to the long, relatively independent history of most of the disciplines involved, we lack the systematic integrated, transdisciplinary, holistic, and in-depth knowledge of the feedbacks between the different parts of socio-environmental systems. In designing (conceptual) approaches to address feedbacks, the issue of scales comes to the fore. The natural, earth, and life sciences have essentially gathered information at local, regional, and global scales and synthesized it to develop models to predict patterns globally. The social sciences and humanities have gathered their information and synthesized it at the local scale. There is thus a need for ways to downscale (provide higher resolution of) environmental information and to upscale the information on societies. The former is complex enough, but inroads are being made in that domain. The latter is much more difficult and probably demands substantive methodological development beyond simple statistical aggregation.

- *Connecting dynamics at multiple scales*. In both the debate on different epistemologies and the discussion of feedbacks, different scales and scalar interactions play important roles. The current world is characterized by global scale changes in Earth system dynamics, emerging from local changes in human interactions with the environment. The emerging global challenges translate into impacts on local realities, and most solutions to manage these have to be implemented at local scales. This brings about the challenge to represent such cross-scale dynamics in modeling tools. Prompted by the fact that for a long time the climate and Earth sciences were the primary disciplines to study greenhouse gases and their consequences at the global level, the efforts of the United Nations were directed at finding global solutions to these challenges, for example suggesting the creation of a $100 billion Green Climate Fund. But in doing so, they did not take into account that this involved different cultures, different societies, and different economies. What was proposed was a uniform solution, a united effort of burden-sharing to avoid irreparable damage to our environment. If, on the other hand, the challenge is seen not as an environmental one but as a societal one, then it is clear that not all societies can deal with it in the same manner. As a result, the Green Climate Fund has only raised $30 billion a year. Introduced in the run-up to the 2015 United Nations Climate Change Conference (COP 21), the trend of allowing different societies to define their own contributions to mitigate climate change is, from that perspective, an improvement. To use models to assist in finding potential solutions to these challenges requires the capacity to represent the local societal dynamics in the context of global processes, and vice versa.
- *Codesigning models*. While models are mostly used as tools for researchers aimed at expanding their mental capacity to explore system functioning, new perspectives and demands on modeling are emerging in terms of the interactions between the users and creators of models and society as a whole.

Figure 6.1 provides an overview of different ways in which science and society may interact in the context of the design and use of models. Such codesign and coproduction of research has become important in global change research (Cornell et al. 2013), with repercussions for modeling. Codesign of research questions may change the nature of the questions and, therefore, have consequences for the suitability of the modeling tools available. While many

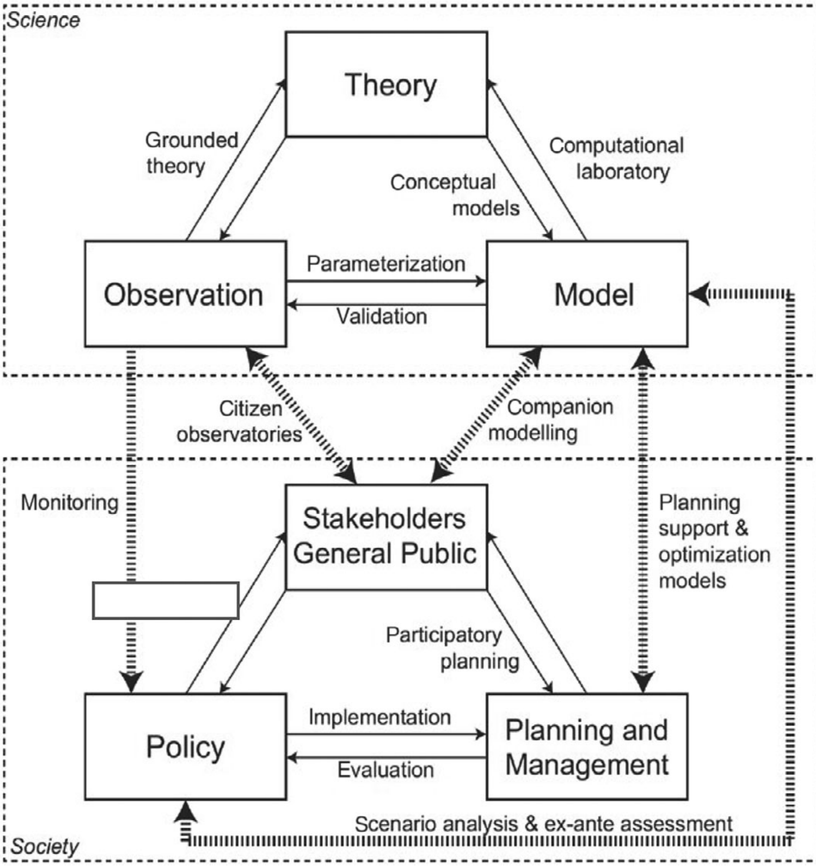

FIGURE 6.1 Schematic representation of codesigned modeling. (Source: Verburg et al. 2015, published under CC-BY-4.0)

modeling tools are built from the perspective of exploring system function, they may not be able, or are not optimally designed, to answer questions that emerge from the interactions between researchers and stakeholders. Research models need to be transformed into operational models so that choosing the right model for the question at hand becomes even more important (Kelly et al. 2013). Apart from codesigning models to better address societal questions, codesign should also involve data-gatherers and non-modelers in the design process. This way, model design can be better matched to available data and data collection to the needs of the model.

- *Modular architectures*. Most models are written to be stand-alone. The disadvantage is that investments in redesigning all model components make the development of new models extremely expensive. To tackle the challenges outlined in this chapter a diversity of approaches is needed. Component-based modeling brings about the advantages of "plug and play" technology. Models wrapped as components become functional units that, once implemented in a particular framework, can be coupled with other models to form applications. Frameworks and architectures additionally provide the necessary services such as regridding tools, time interpolation tools, and file-writing tools. A model component can communicate with other components even if they are written in a different programming language (Syvitski et al. 2013). Plug-and-play component programming benefits both model programmers and users. Using this framework, a model developer can create a new application that uses the functionality of another component without having to know the details of that component. Models that provide the same functionality can be easily compared to one another simply by unplugging one model component and plugging in a different component. Users can more easily conduct model intercomparisons or build larger models from a series of components to solve new problems. To ensure that one model's output variable is appropriate for use as another model's input, a precise description of the variable, its units, and certain other attributes are required.
- Finally, we need to consider the *position of the modeling effort* in the chain of actions that leads to understanding the dynamics. Generally, thus far, in developing prognoses about the future, models have been positioned at the end of an argument that is built upon scientific understanding of extant conditions and drivers of the trends. But following what has been said about ex ante models, what would happen if models were taken as the starting point of the argument? Rather than present deviations from an existing trajectory, they could then inspire scientific research toward a better understanding of potential futures and their implications, including potential unintended consequences. This is the domain of scenario analysis.

Scenario Building

The other main tool that we have in thinking about the future is "futuring" or scenario-building. This is an approach that was initiated by Shell PLC at the time of the first oil crisis (1973). It has since been developed in a wide range of domains driven by the long-term planning requirements of certain industries (energy, reinsurance), and adopted by governments (e.g., Singapore, Dubai) and supranational institutions such as the World Bank. But it has also played an important role in thinking about sustainability, more or less in parallel with the development of modeling, such as for example in the work of the Intergovernmental Panel on Climate Change (IPCC); see the various IPCC reports (e.g., Nakicenovic & Swart 2000) and the global research program "The World in 2050" (Sachs et al. 2018), and also the various projects about transitioning from the present to more sustainable futures, such as Hammond's "Which World?" (2000). Futuring is currently emerging as a discipline in a limited number of institutions in the academic world. It uses a mixture of modeling and scenario analysis techniques to coherently develop multiple perspectives on the future. In view of its increasing importance in considering futures, scenario analysis merits some attention.

Scenario design and scenario analysis are based on the assumption that anticipation is an oft-overlooked or ignored capability that we need to operationalize and use in the present situation. After all, we always talk about feed*back*, but only rarely about feed*forward* (Nicolis n.d. presents an early discussion), a point recently made very convincingly for economics by Beckert (2016). It begins by qualitatively imagining a number of potential futures along the lines presented at the end of the last section, focusing first on futures which are the result of out of the box thinking and thus disconnected from the present, and then considering the plausibility of these. As these potential futures are analyzed and detailed, flesh is increasingly added to the various skeletons.

This is an exercise in imagining and logically analyzing the implications of alternative possible outcomes. It does not try to show one exact picture of the future. Instead, it deliberately presents a number of alternative futures and the roadmaps leading to them. In contrast to prognoses, scenario building and scenario analysis do not use a conscious extrapolation of the past. They do not rely on historical data and do not expect past observations to be valid in the future. Instead, they try to consider a wider range of possible developments and turning points, which may (but need not) be loosely connected to the past. In short, several scenarios are demonstrated in a scenario analysis to show possible future outcomes that can serve as goals to be pursued. It is useful to generate at least a combination of an optimistic, a pessimistic, and a most likely scenario, but a wider range of fundamentally and structurally different scenarios can also be useful.

Scenario analysis is different from modeling, but widely uses models. Models are often used to build scenarios, but scenarios are also often used to begin the process of model building. In the former case, the model is the link between the present and the future, and the forecasting scenarios are extrapolated from the models. In the latter case, the scenarios are exercises at designing out-of-the-box futures, and models are used to link the future with the present through back-casting.

What would the development of scenarios for analysis entail? In outlining this, I follow the paper by Bai et al. (2015) mentioned earlier. It should include recent advances in cognitive science, asking how the cognitive categories are formulated, and how decisions are made, both individually and collectively. Among other things, this would open up the question of the relationship between feedback and feed-forward (anticipation), which is fundamental to human behavior (we all live between past and future), but which has thus far not been given its due in how we model or construct scenarios (Montanari et al. 2013; Sivapalan et al. 2014). It would also imply exploring the role of creativity, intuition, and imagination in how to deal with uncertainty. Thus far, reductionist science has generally left these questions alone, or at least not studied them scientifically or integrated them in our scientific perspective on the world. Arthur (2009) broaches this issue at the interface of technology and economics, which can be extended beyond those domains into the wider study of all our cultural and social institutions. What drives innovation in those domains? Are invention and innovation stochastic, as is often argued, or not (Lane et al. 2009)? These remain open questions until we have a better understanding of the possibilities for facilitating innovations, and the spaces within which innovations occur (see Chapter 12).

Exploring multiple dimensions of innovation spaces is challenging but essential. One approach I mentioned earlier is to take a set of phenomena and project them into a high-dimensional space to identify a large number of potential relationships between them (Fontana 2012). The space is then reduced to fewer dimensions by determining which of these relationships cannot explain the phenomena at hand. Coupled with the enhancing capacity to collect and relate big data, this might be a fruitful path to reduce the path dependency of scenario development. Computing power can in principle be used not just to reduce complexity (as in the case of statistical methods), but also to increase it, if the appropriate software is developed. A reconceptualization of the role of scenarios also includes a review of the field of economics, where discussion is often predominantly about the allocation of resources within existing (technological, social, institutional, and environmental) structures. For an excellent and, detailed discussion of the need to include anticipation in economic reasoning, see Beckert (2016).

But in order to achieve desirable futures, more fundamental questions need to be asked as well: How did the structure come about, and how might it change? What are the regulatory mechanisms involved? What happens when an existing structure becomes more and more complex? Does it become more efficient and/or resilient? What does that mean for its adaptability, its capacity to change? A promising emergent field of study is therefore the attempt to bring evolutionary thinking and complex systems approaches together with behavioral and other kinds of economics and organization science in the design and analysis of scenarios (see Wilson & Kirman 2016).

Regrettably, for all the potential power of scenario building and scenario analysis, as for example shown in the work of the Oxford (www.sbs.ox.ac.uk/faculty-research/strategyinnovation/oxford-scenarios-programme-0) and Singapore (www.csf.gov.sg) futuring centers, or in the many scenarios developed by business, finance, and non-governmental organizations, this approach has not yet reached a degree of maturity in academia that is sufficient to include it centrally in our most current toolset to think out of the box about multiple sustainable futures.

For one, a broader use of scenarios in public deliberations and collective decision-making would involve the option to explore multiple potential futures with the situated knowledge of multiple stakeholders (see Wilson & Kirman 2016). But part of the challenge seems also to be that in the communities where they are used, many scenarios are too smooth, too formulaic, too predictable, and do not open up the full gamut of expectable and unexpected consequences of our choices between trajectories to move forward into the future. They seem not to be fully integrating the implications of conceiving the challenges in front of us in different domains as true complex systems, and are therefore subject to ontological uncertainty. Developing more advanced models would benefit from an academic effort that is not directly and immediately linked to applications in the real world and could delve into many advances in fields such as political, social, and cognitive science, including the idea that our individual choices are primarily determined by our emotions, rather than by reasoning, and investigations into the dynamics responsible for collective decision-making.