Annual Review of Environment and Resources

Scenario Development and Foresight Analysis: Exploring Options to Inform Choices

Keith Wiebe,[1] Monika Zurek,[2] Steven Lord,[2] Natalia Brzezina,[3] Gnel Gabrielyan,[4] Jessica Libertini,[5] Adam Loch,[6] Resham Thapa-Parajuli,[7] Joost Vervoort,[2,8] and Henk Westhoek[9]

[1]Environment and Production Technology Division, International Food Policy Research Institute, Washington, DC 20005, USA; email: k.wiebe@cgiar.org

[2]Environmental Change Institute, University of Oxford, Oxford OX1 3QY, United Kingdom; email: monika.zurek@eci.ox.ac.uk, steven.lord@eci.ox.ac.uk

[3]Sustainable Food Economies Research Group, KU Leuven, 3001 Leuven, Belgium; email: natalia.brzezina@kuleuven.be

[4]Charles H. Dyson School of Applied Economics and Management, Cornell University, Ithaca, New York 14853, USA; email: gg352@cornell.edu

[5]Applied Mathematics Department, Virginia Military Institute, Lexington, Virginia 24450, USA; email: libertinijm@vmi.edu

[6]Center for Global Food and Resources, University of Adelaide, Adelaide SA 5005, Australia; email: adam.loch@adelaide.edu.au

[7]Business School, Faculty of Business, Law and Politics, University of Hull, Hull HU6 7RX, United Kingdom; email: r.b.thapa-parajuli@2014.hull.ac.uk

[8]Copernicus Institute of Sustainable Development, Utrecht University, 3584 CS Utrecht, The Netherlands; email: j.m.vervoort@uu.nl

[9]PBL Netherlands Environmental Assessment Agency, 2500 GH The Hague, The Netherlands; email: Henk.Westhoek@pbl.nl

Annu. Rev. Environ. Resour. 2018. 43:545–70

First published as a Review in Advance on May 31, 2018

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-102017-030109

Keywords

scenarios, foresight, agriculture, environment, climate, decision making

Abstract

In an increasingly globalized and interconnected world, where social and environmental change occur ever more rapidly, careful futures-oriented thinking becomes crucial for effective decision making. Foresight activities, including scenario development, quantitative modeling, and scenario-guided design of policies and programs, play a key role in exploring options to address socioeconomic and environmental challenges across many sectors and decision-making levels. We take stock of recent methodological developments in scenario and foresight exercises, seek to provide greater clarity on the many diverse approaches employed, and examine their use by decision makers in different fields and at different geographic, administrative, and temporal scales. Experience shows the importance of clearly formulated questions, structured dialog, carefully designed scenarios, sophisticated biophysical and socioeconomic analysis, and iteration as needed to more effectively link the growing scenarios and foresight community with today's decision makers and to better address the social, economic, and environmental challenges of tomorrow.

Contents

1. INTRODUCTION

The world today is becoming ever more interconnected, and the challenges we face are ever larger and more complex. Human-driven environmental change is taking place at an unprecedented rate (1), and geopolitical and technological change add to the complexity and uncertainties. Examples appear daily in the popular press as well as the academic literature. What will driverless vehicles mean for road safety and energy demand (2)? What effect will poverty and climate change have on migration patterns (3)? How can we feed the world in 2050 (4, 5)? Can we meet the targets of the Paris Climate Agreement? Can we achieve the Sustainable Development Goals, and what happens if we don't? The short answer is usually "it depends"—on the choices we make and how they interact with forces beyond our control. But given the complexities and uncertainties involved, how can we go beyond the short answer to a more meaningful understanding of these choices and interactions as they might play out over the longer term?

Simply put, foresight is the act of thinking about the future to guide decisions today. All of us engage in foresight every day. Will I need an umbrella today? Will road conditions slow my commute? Given ever-easier access to weather forecasts and traffic information, and quick consideration of possible options and outcomes, these decisions are relatively simple. But when we confront questions involving longer time periods and larger groups of people, the complexities and uncertainties quickly become much greater and more consequential. Issues such as these are inherently multiscale in social, spatial, and temporal dimensions and thus require more careful consideration—not only in terms of what questions are raised and how they are addressed, but also in terms of who is involved in the process. This is where more formal and systematic foresight exercises involving scenario development and analysis can play an increasingly important role.

2. THE ROLE OF SCENARIOS AND FORESIGHT

In this section, we examine the nature and purposes of scenarios and foresight, and review how their use has evolved over the past century in a wide range of applications.

2.1. Predicting, Exploring, and Envisioning

As the future is a vast subject, so too the term foresight covers a diverse set of activities. Depending on the time horizon and the level of complexity and uncertainty that characterize a particular question of interest, foresight may rely primarily on factual information, active speculation, or a wide range of intermediate tools and approaches (**Figure 1**).

Scenarios are specific representations of the future to facilitate thinking about the possible consequences of different events or courses of action within a systematic foresight exercise. For example, the Intergovernmental Panel on Climate Change (IPCC) defined a scenario as a "plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships" (8, p. 86).

The literature generally splits scenarios into three broad categories, depending on their nature and purpose and on the degree of complexity and uncertainty involved (9). Predictive scenarios use knowledge about the past to derive probabilistic estimates of alternative future conditions (10). Exploratory scenarios start from the present and explore the impacts of various drivers, trends, and interactions from now into the future. Normative scenarios start from a particular desired vision of the future and work their way backward to identify pathways for reaching this future. But this basic classification is not universal, and debates continue about distinctions between scenarios and their qualitative and quantitative framings (11, 12). Further distinctions and overlapping terms also complicate discussion. For example, the term forecast is commonly used to describe a predictive exercise that identifies a most likely future, as in shorter-term contexts such as monthly market forecasts, whereas the term projections is often used to describe the results of scenarios without assigning probabilities to the different outcomes.

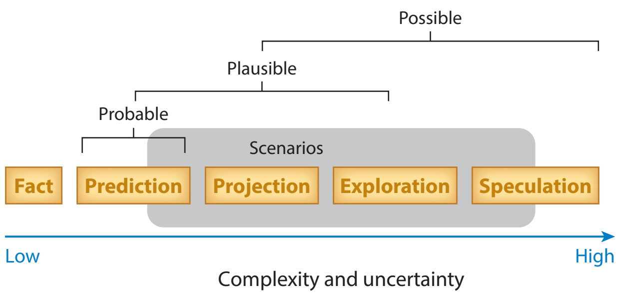

Figure 1

Approaches to scenarios and foresight include prediction, projection, exploration, and speculation, and involve differing degrees of complexity and uncertainty. Figure adapted from References 6 and 7, with permission.

2.2. The Evolution of Scenario Use

Diverse communities have long used scenarios to explore the effects of potential future developments and inform robust planning, ranging from foreign policy and defense (dating back more than a century) to the business community and environmental and resource analyses (13, 14). Areas such as international relations and business face large uncertainties in a medium time span (e.g., 5–20 years); anticipating major shifts in the business environment is crucial, and at this point traditional shorter-term forecasts fail (15). However, areas such as demographic and global environmental change (including land-use change) are characterized by lower uncertainty in the short range (1–5 years), but with widely diverging paths on a longer time scale. Foresight offers different advantages in each case.

2.2.1. Defense. One of the earliest examples of scenarios as a formal planning tool is in defense, where scenarios are generally referred to as war games. In the *Art of Wargaming*, Perla (16, p. 164) defines war games as "a warfare model or simulation whose operation does not involve the activities of actual military forces, and whose sequence of events affects and is, in turn, affected by the decisions made by players representing the opposite sides." Although they are described as games, these exercises are taken very seriously and recognized by military leaders as having great value and providing educational benefits beyond the output of computer simulations (17). In a war game, the player roles are typically filled by the persons responsible for making decisions in the real world. This means that as the game is played and replayed, the participants gain intuition about the battlespace or problem dynamic that would not be acquired in a briefing of simulation outputs (17–20). For this reason, war gaming has been an integral part of the US Naval War College curriculum since 1903, and the War College continues to be the global center of war gaming research today (18).

War games allow military decision makers to analyze problems that cannot be understood from a purely mathematical perspective because they involve the uncertainty of human decisions. As Hanley (21) contends, they are a weakly structured tool for a weakly structured problem that allows for uncertainty beyond what can be explored even through stochastic models or Monte Carlo simulations. For example, a small-scale war game might help shed light on the effectiveness of a particular concept of operations with "humans in the loop" for launching counterattacks; this type of war game directly addresses how humans interface with the equipment they use, whereas computational simulations often provide the optimal capabilities of the radars, missiles, and other equipment (22). In today's battles for hearts and minds, the flow and impact of information are critical to many operations, and although a war game may not accurately predict the outcome, repeated war games have the potential to inform the decision makers about the possible outcomes (23). Another desirable outcome is that war games allow the decision makers to come to consensus organically as they explore the impacts of their decisions together over the course of the day or week of participation (17, 24).

Despite the long history of the use of war games, they continue to evolve to cover new areas and to couple with other defense analysis tools (25). There is ongoing work to hone the cycle of problem solving that involves the use of war games, physical operational exercises, and computer simulations, allowing the results of each prior test to shape the development of the next (17).

2.2.2. Business. Scenario use in the business community is associated with strategic planning (26) and the development of responses to long-term trends outside the horizon of business-as-usual daily operations or sudden disruptive changes to the operating environment. The techniques adapted to business needs grew out of policy and defense work in the 1950s and 1960s. Pioneered by Shell and General Electric, exploratory- or intuitive-logics-type scenarios entered mainstream business use from 1973 onward (26, 27). Also during the 1970s, French companies pioneered the use of normative scenarios under the influence of the French *La Prospective* school of practitioners (28).

Scenario use in business ebbs and flows (29). The 2015 Bain & Company management tools survey indicates that 20% of its 13,000 business respondents use scenario planning, down from 70% eight years earlier (30). Studies have attributed the value of scenario planning to business in terms of secondary effects such as fostering conversation, adopting alternative perspectives, enhancing understanding, and creating the ability to shape the future (31). There is little research, however, or direct validation that scenario planning improves long-term business performance (32, 33). Reasons cited include the inherent difficulty of measuring qualitative and quantitative outcomes from a foresight practice, and a lack of standardized tools (31, 34). Reviews in business literature continually point to an unbalanced research focus on methodology in the scenario field and not enough tools for evaluation (34).

In terms of business use of scenarios and environmental resources, use is neither standardized nor obligated in environmental impact assessment and associated tools (35). However, the use of alternative future scenarios is increasingly viewed as best practice from industry bodies and environmental agencies (36, 37). Lloyd's insurance group, for example, commissioned a study by agriculture experts and economic modelers on the impacts of an extreme shock to the global food supply "in order to explore the implications for insurance and risk" (38, p. 2).

2.2.3. Environment, agriculture, and food. Although defense and business led in the early use of scenarios, applications to the environment have increased rapidly in recent years. A keyword search of the scientific database SCOPUS using the keywords "uncertainty," "scenario," and "future" identified 3,161 articles published during the period 2013–2017. Almost 60% of these articles were in the fields of Environmental Sciences and Earth and Planetary Sciences, whereas only approximately 5% were in fields such as Business, Management, and Accounting. Although these results could be biased because the business community may publish their scenario work less often in scientific journals, they nevertheless indicate the extensive use of scenario work in environmental fields.

Applications of scenarios have increased among environmental and resource decision makers, consultants, and researchers as tools for dealing with the complexities and uncertainties associated with various challenges at various levels, from local to global (14), and for informing the necessary steps toward achieving desired collective management goals (9, 11, 39). Uncertainty about future environmental or resource constraints is a significant motivation for using scenarios to make decisions across various aspects of the political world (40, 41). Governments may use scenario planning to better cope with future uncertainties that will affect humans and the environment at scale. For example, planning for a changing climate and any associated limits to agriculture and food systems is currently a major concern for many policy makers and international organizations.

In environmental and resource science, using scenarios to explore options and inform choices usually takes the form of alternative or multiple futures designed through a foresight process and the evaluation of the performance of decision options across multiple futures (42). The aim is to produce options that are robust to alternative future conditions (43, 44). Feedback on the failure of options across diverse future conditions is used to adapt options or explore new options, guided by the rationale of improving robust performance to alternative futures (45). Environmental and resource science also uses predictive scenarios in risk and decision analysis. The term scenario is a central part of the definition of risk (46). In this use of scenarios, options are explored and choices informed based upon the rationale of minimizing risk. Scenarios may also be used to involve stakeholders and decision makers in raising awareness about complex issues or resolving conflict between divergent interests.

Some researchers use scenarios in a broader context (47), but often scenarios are applied to specific fields in particular regions; for example, land-use models in Tanzania (48) and China (49), water in Italy (50), environment–food trade-offs in Latin America (51), the organic food market in Europe (52), environmental assessment in the United States (53), and the impact of the increase of genetically modified products in European agriculture (54).

Scenarios are increasingly used with quantitative food-systems models to deal with uncertainties about food supply and demand in the future (55), and they have played a critical role in analyses prepared for the IPCC (56). A burgeoning literature explores the interdisciplinary nature of food systems with relation to climate change (57–60). Much of this work draws on linked biophysical and economic modeling, using increasingly sophisticated data and models (see Section 3.4.4). As von Lampe et al. (61) and Nelson et al. (62) note, however, results depend heavily on the analytical approach, including model structure and parameter selection, which can vary from study to study. This dependence further creates uncertainty that calls for closer interdisciplinary collaboration (63). One such effort to compare and improve quantitative models with particular focus on the impacts of climate change on agriculture is the Agricultural Model Intercomparison and Improvement Project (AgMIP), to which we return in Section 4.2.

3. THE FORESIGHT PROCESS

Previous sections have considered what scenarios and foresight are used for. Equally important are the questions of who is involved in scenarios and foresight exercises and how they do it. These depend on what the scenarios and foresight exercises are for, and how the results are to be discussed and used. More generally, how can appropriate representation be ensured to balance diverse, complex, and possibly competing interests? This is especially important and challenging when scenarios and foresight are used to inform decision making about prioritization and resource allocation—that is, when decisions have real consequences not only in the future but also in the present, particularly when the outcome involves trade-offs between the interests of different stakeholders. In such situations, how can goals of simplicity and transparency be balanced against participation and completeness?

Foresight exercises typically include several basic steps to address the complexity and uncertainty inherent in bigger questions about the future (**Figure 2**). These generally begin with a set of questions or challenges that confront a particular group of people; a process of dialog to identify key concerns and involve key stakeholders; consideration of alternative options or scenarios; analysis of the likely impacts of those alternatives; and, eventually, decisions about the best course of action—after which the process may begin anew.

Different exercises may emphasize some steps more than others, or exclude some steps altogether. Informal foresight, as in the simple examples we provided in Section 1, may proceed directly from questions to simple scenarios, quick analysis, and then decisions. More formal foresight processes may involve extensive dialog among stakeholders and more deliberate scenario design (focusing on the steps in the top half of **Figure 2**), but may vary in the way and extent to which the implications of those scenarios are analyzed. By contrast, academic research may also involve foresight, but with less attention to dialog and more focus on formal analysis (emphasizing the steps in the bottom half of **Figure 2**). The appropriate approach and balance between the various elements depend on the nature of the question, the magnitude of the potential consequences, and who will be affected. We examine these issues in greater detail in the following sections.

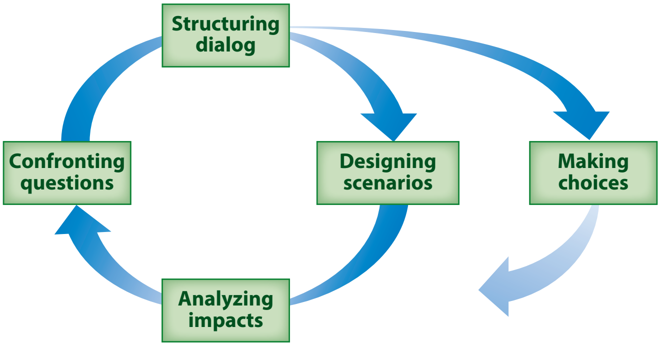

Figure 2

Key steps in the foresight and scenario development process include dialog, scenario design, analysis, and decision making.

3.1. Confronting Questions

Questions about the future, such as those that we discussed in our introduction, are the starting point for any foresight process. Whether such questions are easily answered or call for a more formal and systematic foresight process depends on a variety of factors, including the nature of the question, the potential magnitude of its implications, whether choices today may affect those implications, and who is involved—whether they are individuals with power to make those choices or parties who may be affected by those choices, or both. In general, the larger the number of people is who have a stake, the longer the time horizon is, and the greater the complexity and uncertainty are, the more likely that a structured foresight process will be needed if alternative courses of action and their likely consequences are to be carefully considered. Although confronting questions is the first step in a formal foresight process, those questions may be clearly articulated only as the parties involved engage in a more structured dialog process.

3.2. Structuring Dialog

Many scenario processes include stakeholders in the actual scenario development, often with the intention to create ownership and saliency and maximize the impact of the scenario analysis. How to structure the dialog with stakeholders, who the actual scenario builders are, and to what degree to involve stakeholders versus creating expert/scientist scenarios depend on the purpose of the actual exercise (exploration, awareness raising, or decision support) (see 64, chapter 5). Stakeholders can be involved in various ways: Experts may build scenarios in consultation with different stakeholder groups, experts may codesign scenarios with stakeholders who contribute as part of the team, experts and stakeholders may jointly build scenarios through a process of "codecision," or stakeholders may take full ownership of the scenario development process (64).

Particularly for scenarios created for decision support it is important to include a variety of stakeholders, if possible including those who are likely to be affected by the issue at hand, those who can affect the outcome by their actions or inaction, and those who can help with or conduct analysis of alternative scenarios. Identifying the relevant scenario developers is therefore not trivial but can be the major determinant for the success of the whole exercise. As scenario development can also provide a space for conflict resolution, particularly on politically charged issues, the selection of stakeholders to involve should be based on a systematic stakeholder mapping and analysis exercise.

Game playing is an increasingly common method for portraying and testing different scenarios. Within a constructed environment, stakeholders (including policy makers and managers) can be exposed to a variety of different scenarios and outcomes that relay the results of their previous individual or collective choices. In this environment, they can feel safe to test different approaches and "break the system" to identify possible parameter limits. In the same way, learning can also take place.

3.3. Designing Scenarios

Designing appropriate scenarios requires consideration of the purpose of the foresight exercise, the questions to be addressed, the spatial and temporal scales involved, and the resources available, among other factors. We consider these issues in turn.

3.3.1. Creating versus customizing. When using scenarios for a specific policy or strategic question, an important question is whether to design new scenarios specifically for that purpose or use existing scenarios that were developed for other purposes. The benefit of using existing scenarios is that they may offer significant content and analysis that do not have to be created from scratch. Furthermore, although scenarios are often used to provide a wider context for lower-level planning, or for specific issues or challenges, many of the drivers and interactions in an existing scenario set may be relevant to the new questions of interest. However, using an existing set of scenarios poses the significant risk that these scenarios may frame the exploration of future uncertainties in a biased fashion by highlighting some challenges and ignoring others.

One way to deal with this dilemma is to combine the benefits of existing scenario sets and the benefits of creating new scenarios through a process of scenario adaptation and customization (45). To do this while avoiding preframing by the existing scenario set, a scenario process can start with creating a mapping or listing of all relevant contextual concerns to the question, identifying a plan or strategy to investigate, and only then introducing existing scenarios. These scenarios are then reviewed through the map or list of relevant concerns, and adapted or elaborated on these points. Furthermore, scenario sets can also be designed with adaptability and customizability in mind. In the Future Scenarios project of the Climate Change, Agriculture and Food Security (CCAFS) program of the CGIAR, future scenarios are designed at the regional level by stakeholders from countries in that region to help address policy concerns in those countries. This is done by including a wide range of drivers in the scenario structuring process beyond what is normally done, and including multiple analytical models to quantify the scenarios, offering a wider range of projections that make the scenarios relevant for diverse policy concerns (65, 66). We describe this process further in Section 4.3 below.

3.3.2. Levels and scales. Scale is an essential concept for scenario research and scenario-based planning (67). Scale refers to spatial, temporal, and other dimensions of analysis, whereas levels represent specific positions on a scale (68, 69). Because scenarios are often used to investigate contextual conditions for specific policies and strategies, one of the functions of scenarios is to bring in concerns and drivers operating at higher levels to allow scenario users to work out how these dynamics might affect the success of their plans or the state of the system they are investigating. Higher-level (such as global) scenarios can be used as a context for national or local-level planning. The above remarks about customization are relevant to scenario down-scaling.

A growing body of literature investigates cross-level links between scenario sets. In terms of the scenario content, Zurek & Henrichs (6) recognize different degrees of connectivity. These include scenario sets that are equivalent between different levels (which are essentially the same scenarios imagined at different levels of geography or governance), consistent scenario sets (which are linked in terms of their main assumptions), coherent scenario sets (in which the scenarios explore the same logic, paradigms, or basic archetypes, but play out differently at each level), scenario sets that are merely comparable in their scope, and independent scenario sets that have differing scopes of interest.

Different degrees of connectivity also exist in terms of how the scenario development processes are integrated. What is notable is that many cross-level scenario exercises work in a top-down mode, using contextual scenarios to frame lower-level planning (70, 71). Bottom-up scenario processes that try to aggregate many local perspectives on the future into macrolevel scenarios are still rare (72). The choice of connectivity across levels in scenario sets should be made based on what the purpose of the process is, how much specificity is required for each level to which the scenarios are applied, how important a sense of co-ownership by participants is at different levels, and how compatible the different levels are in terms of scenario concerns in the first place. Our recommendations for scenario adaptation apply to cross-level scenario sets; in most cases, consistent, coherent, or comparable scenario sets are expected to be desirable, as they offer contextual perspectives while allowing for the cocreation of knowledge about level-specific concerns (66).

3.3.3. Risk scenarios versus exploratory scenarios. Using scenarios for risk analysis in environmental and resource science requires a comprehensive scenario set, or risk scenarios, in the sense that all futures that may cause harm as defined by the study are accounted for, and the probability of their occurrence can be estimated with a known degree of confidence. Risk analysis struggles to build and validate comprehensive scenario sets (73). Vulnerability or conditional risk is commonly used, where the condition or assumption imposed is that the future will be one of the scenarios that are being considered (74).

Without the constraint or belief that a comprehensive or conditionally predictive scenario set can be built, exploratory analysis suffers from challenges in the other direction. What is the relevance if the options perform robustly to conditions that no stakeholder believes will occur, or if the chances of those conditions occurring cannot be estimated? Exploratory analysis must make the argument that the alternative futures used, although not predictive, are a proxy for the kind of features that will test an option in the future. The term plausibility is often used in this regard, but it is not sufficient by itself. The foresight field is still divided by an ongoing debate concerning probability and plausibility (12). New methods are emerging, such as robust risk analysis (75), but they require more technical knowledge for researchers and practitioners.

In the past five to ten years, the banking and insurance sectors have led the development of an intermediate category of scenarios broadly between predictive and exploratory. They usually do not focus on the uncertainty in long-term futures, but uncertainty in complex conditions. Scenarios are chosen according to their high impact, but a method for choosing a diverse set of scenarios commonly used in exploratory scenario analysis is employed to develop a small set of diverse high-impact scenarios. Stress scenarios can be used for robust analysis of options (stress tests); or, if the condition of high impact is assumed, one could argue for a conditional risk analysis of options. Environmental and resource science has yet to widely employ stress scenarios.

3.3.4. Choosing among possible scenarios. Scenarios for environmental and resource decision making involve social, technological, economic, environmental, and political factors over long time frames and potentially different scales and levels, as noted above. Given this wide array of possible dimensions, a first task is to combine trends and disruptions in these factors into plausible and relevant representations of the future, considering appropriate scales, levels, and stakeholder interests as noted above. Given that there may be thousands, if not millions, of futures so represented, a second critical task is to select a subset that are most important and useful for decision making. These are not necessarily the most likely or the most preferred; both selection criteria and selection number depend on the purpose, method, and design of the scenario study.

Selection criteria. For exploratory scenario studies, the selected set should be maximally diverse to maximize the span of potential futures considered. This aligns with the goal of using exploratory scenarios to test the robustness of policy plans. For example, strategic scenarios regarding the former Soviet Union were criticized for being too constrained to conceive and investigate the dynamics of the Soviet Union's collapse (76). Selection using diversity criteria has been formalized and implemented in software tools, e.g., the Scenario Diversity Analysis (SDA) method (77), which is generalized by the Optimized Linear Diversity Field Anomaly Relaxation (OLDFAR) tool (78). Analysis of the *Special Report on Emissions Scenarios* (SRES) storylines (57) using these tools concluded that they are not maximally diverse storylines (77).

For risk studies, the selected set should minimize the loss of information about the distribution of future impacts. For example, a scenario discovery method developed by RAND (79) selects scenarios that populate the tail of the distribution of extreme impacts. Selection on risk, which will include scenarios that are very unlikely if they have extreme impacts, should be distinguished from a probability selection method as in *La Prospective* (26). A probability method identifies the trajectory of factors in the most likely futures, which is not valid for risk analysis but is valid when the goal of the study is to shape those most likely futures toward a normative goal.

For stress test studies, the purpose is selecting scenarios that stress the system in different ways. Conceptually, stress scenarios have more focus on impact than exploratory scenarios but are not an attempt to be as comprehensive as required in a risk analysis. A new version of the scenario discovery method combines selection criteria, selecting for both extreme impact, the "stress" part of a stress scenario, and diversity, which captures the "different ways" (80).

Selection number. Minimizing the loss of the span of potential futures, or the loss of information about extreme impacts, can, at least theoretically, be achieved with large scenario sets. Communication purposes and computational limitations of either humans or machines usually result in a small number of scenario sets, often between four and eight (78), although these may involve multiple variants, for example, those based on different choice of climate or crop modeling tools (62, 81). Even for robustness analysis using exploratory scenarios, loss of information in such a downscale and the potential for perceived arbitrariness in the selection remain weaknesses of scenario methods. Selection criteria counter this somewhat with scientific rationale and a repeatable method. The OLDFAR method (78) was designed to counter arbitrariness, but no conducted scenario process (in which selection is just one step) has yet used multiple selections (e.g., four diverse selections of four diverse scenarios, which would be more robust than using current algorithms to generate a set of sixteen diverse scenarios). Working with large scenario sets (from hundreds to thousands of scenarios) has been done in defense and engineering risk applications (82), but it has barely been developed in environmental and resources studies. This is due to the complexity of scenarios used in environmental and resource studies, which typically require human expertise to describe the effects of social, technological, economic, environmental, and political factors on the system in question. To our knowledge, there is a lack of established interfaces allowing humans to interact with large numbers of scenarios in workshop settings or within the limited resources of research projects.

3.3.5. Standardization. Standardization of scenarios prevents duplication of effort, and increases interoperability and comparison between studies. It also fosters support mechanisms for updating scenarios, and allows smaller firms and public institutions to conduct foresight where they might not have been able to do so previously (83). But scenario planning has been described as being in a state of methodological chaos (34). Scenario planning is generally a continuous process, whereas scenarios are usually generated in one-time exercises. At present in the environmental sciences, for example, there are a plethora of scenarios developed in individual studies or by individual projects in the period 2005–2015, with time frames to 2030 or 2050, whose premise has subsequently become outdated because of events such as Brexit.

It is generally recognized that the use of technology for standardizing knowledge bases, structuring exercises, designing scenarios, and communication is underutilized (84). There are ongoing efforts to generate standardized scenarios in various fields, and to standardize methodology. Formal frameworks for environmental assessment have been proposed (36), but as yet none has been adopted. Environmental studies either develop one-shot scenarios independently or they use scenarios that have become standard, such as what occurred through the IPCC promoting the use of SRES (57), Representative Concentration Pathways (RCPs), and Shared Socioeconomic Pathways (SSPs) (56, 85–87) representing alternative trajectories for greenhouse gas emissions and key socioeconomic variables. Institutionalization of foresight is increasing in international agencies such as the European Commission, leading toward a slow convergence in methodology, and multimodel studies using RCPs and SSPs are increasing through AgMIP, which is described further in Section 4.2. Nevertheless, the amount of standardization remains low compared with the financial sector, where stress testing has been driven by the need to meet regulatory guidelines (88). Agencies such as the European Insurance and Occupational Pensions Authority (EIOPA) and US actuarial societies develop economic scenario generators, guidelines, and data sets that are the basis for stress testing across the sector (89).

Despite its advantages, standardization also carries risks, by limiting the potential for exploration. In climate science, scenarios based on standard RCPs and SSPs are useful for modeling the impacts of climate change, but this may not apply across all environmental and resource areas. For example, there are concerns regarding whether the SRES or SSP narrative scenarios are too constrained to capture the further drivers and factors involved in a more complete analysis of the impacts of climate change on outcomes such as food security (77). Efforts to refine these scenarios continue as they are quantified in specific models for specific applications, as noted in Section 4.1.

3.4. Analyzing Impacts

As we have shown, the process of scenario design moves from discussion of key drivers and trends to more explicit identification of assumptions and logical relationships. The precise nature and extent of the latter step depends on the analytical approach to be used.

3.4.1. Linking qualitative and quantitative approaches. Story and simulation (SAS) is currently the main approach for linking qualitatively designed future narratives with quantitative modeling of environmental or economic variables (90–92). In SAS, the qualitative process first sets out alternative narrative stories as outlined above (93). These in turn provide the context for setting exogenous parameters that the quantitative models use to perform simulations, beyond human ability, on the complex dynamics of endogenous variables. One of the main examples of this is the use of SRES emission scenarios (and more recently RCPs) to create projections of climate and environmental variables such as temperature and precipitation from global climate models, in combination with SSPs representing alternative narratives and assumptions about population, income, and other socioeconomic drivers in global economic models (57, 87).

Effective scenario planning is attributed to the combination of qualitative and quantitative approaches (94). The two can be highly complementary. For example, the 2016 *World Energy*

Outlook of the International Energy Agency (95) now includes quantitative projections from the World Energy Model (WEM) in the context of three qualitative scenarios. These are a response to the 2007 WEM projections being invalidated by unforeseen events: the 2008 financial crisis, the scale of production of shale in the United States, and Germany's investment in renewable energy. However, once parameterized to the new conditions in 2007, the WEM short-term recession trajectories were trusted more than qualitative outlooks for decision making in energy companies (94).

Linked approaches are a current research front, and coupled approaches beyond SAS represent the state-of-the-art (see Section 3.4.4 below). Use of either qualitative or quantitative approaches exclusively is critiqued and closer integration is called for (34, 96, 97).

3.4.2. Technical issues. Although there is an array of methods to quantify narrative scenarios (98), we focus on the quantification provided by complex simulation models. Within environmental and resource futures there has been little research on the qualitative–quantitative interface with simulation, where narratives are translated into exogenous quantitative assumptions for complex biophysical and economic models. These assumptions generally take the form of numbers specifying socioeconomic variables or indicators such as GDP of regions or nations, population growth, technology change, resource depletion, pollution rates, economic structure, and activity of industrial sectors or populations, at discrete time steps. At each time step the selected exogenous values are fed into computer models, which then calculate endogenous variables such as commodity prices, agricultural outputs, resource stocks, or other outcomes such as risk of hunger, flooding, or resource collapse, depending on the study.

Although there is a range of participatory modeling frameworks and methods in the literature (99), in practice the choice of exogenous assumptions is usually an ad hoc and hand-crafted process performed by researchers familiar with model requirements, rather than stakeholders (100). Stakeholder views transfer by proxy from the qualitative narratives to the representation of dynamic systemic information (variables, inputs, outputs) in the exogenous parameters. Facilitated participatory techniques have been used for indications of directions of change in a list of model parameters in simple formats such as + and –, and indications of rates of change or shapes for the trajectories of variables (65, 101). An example of such a process is the regional scenarios exercise described in Section 4.3 below.

The SAS approach is an integrated modeling approach, but not coupled, and hence can fail to provide fully consistent projections. Given the difficulty of translating qualitative narratives into model parameters, one of the main issues is a potential mismatch between the dynamics generated endogenously in the computer model and the narrative assumptions about exogenous factors. The computer model may compute resource collapse from the settings of the previous time step, for example, but no such collapse may appear in the narrative. More effectively coupling the qualitative "computation" and the quantitative computation has been frequently recommended and featured in the Millennium Assessment scenarios (102). Ideally, quantitative output as calculated from a previous time step should be fed into the scenario-building process to inform the narrative and the variables for the current time step, or, at least, qualitative narratives and quantitative trajectories compared in an iterative process.

Despite existing efforts for improvement (103), coupling qualitative and quantitative approaches is easier said than done. Institutional and cultural factors often segregate qualitative and quantitative teams, complicating the dialog and decision-making processes (Sections 3.2 and 3.5).

3.4.3. Linking biophysical and economic models. Analysis of environmental and resource scenarios is further complicated because on all spatial and temporal scales there are complex and dynamic interactions between biophysical conditions (such as climate, biodiversity, and resource availability) and socioeconomic factors. Modeling the changes in biophysical aspects (such as the concentration of greenhouse gases) therefore cannot be done without taking economic aspects into account; moreover, conversely, economic developments depend on the natural environment. In cases where scarce resources are priced, feedbacks can be modeled using standard demand and supply curves. In the case of externalities (such as pollution, climate change, or impacts on ecosystem services), the effect of biophysical changes will have to be modeled dynamically. Challenges include both spatial and temporal aspects, as the impact of certain economic activities can be more long term as well as spatial (for example downstream). All integrated assessment models therefore have an economic component, as well as a biophysical component, with many interactions between the two. The advantage of such an approach is that the interaction between economy and biophysical conditions can be quantified. Disadvantages include, among others, the complexity of such models, which require long time frames to be developed and tested, and potentially driving large uncertainties in their outcomes. Interpreting and communicating the results of such complex models also requires careful attention.

3.4.4. Dequantification, interpretation, and iteration. The requirement of handcrafted interpretation between qualitative results and setting the parameters for quantitative modeling (also called quantification) is currently a costly process in terms of both money and time. A dequantification step is also required so that model outputs are fed back into the qualitative dialog process. Ideally, a quantitative model would be able to run in a sufficiently short time so that it can provide rapid feedback, but this is rarely possible. Furthermore, it is rarely possible to prerun the model with all possible settings that might be of interest and generate, let alone store, a look-up table of precalculated output values. More typically, the scenario process must iterate multiple times between discrete quantitative and qualitative stages, implying large studies and long development times.

Within the scope of a participatory process, which in some cases might only be one workshop, it becomes difficult to perform even the first integrating step of this coupled process. Frameworks have been suggested (99), but there are no fully satisfactory methods to develop scenarios and capture, according to the expertise and imagination of the participants, a systems-based representation of the dynamics that is complementary to the computer modeling in single-workshop settings with multiple experts and stakeholders. Within the TRANSMANGO EU FP7 project (104), simple causal mapping was used to connect wider environmental and socioeconomic drivers with concrete biophysical and economic modeling parameters such as food prices, but this still required a large amount of interpretation to be made on behalf of the researchers to create exogenous projections.

Recent steps toward improving SAS and linking qualitative and quantitative processes include advances in stochastic mathematical tools such as stochastic dynamical systems, stochastic differential equations, and stochastic networks. Oksendal & Sulem (105, p. 326) note the power of such tools, which allow more nuanced explorations in the face of model uncertainty, and "stochastic differential games involving players with asymmetric information" are an increasingly popular approach to problems in a variety of fields. Nevertheless, although the structure now exists to do better qualitative–quantitative linking, there has thus far been limited engagement between the requisite communities to capitalize on these advancements.

System dynamics models have also been put forward for linking broader environmental and socioeconomic drivers and parameters of more complex computer models. Systems dynamics has been used to develop scenarios and perform quantification for decision support (98, 106, 107), including the literature under the label of so-called fuzzy cognitive mapping (108, 109). Although there are developed frameworks for building participatory system dynamics models (110, 111), there are no established methods for using them as a bridge between stakeholder knowledge about wider drivers and more complex computer environmental and economic models (106, 112). A lack of interaction and cultural issues between qualitative and quantitative communities have impeded their further development.

A promising line of development is using Bayesian networks to bridge between broad socioeconomic variables and computer model parameters. Integrating computer models with Bayesian networks is an established method in environmental modeling and decision support (113–116). This modeling integrates low-resolution representation of broader and more uncertain environmental and socioeconomic drivers and high-resolution computer models. Applications in the cited references are not dynamic (i.e., they do not evolve over time steps as is required for biophysical and economic modeling) and have not been used to develop coupled scenario projections for foresight. Computer models are in effect a synthetic expert that updates information between its inputs and outputs. They are therefore natural objects to use in Bayesian networks alongside statistical models and expert opinion.

3.5. Making Choices

Scenarios can help to inform the general public or specific target groups about important trends. They can provide an approach for structuring, conveying, and illustrating differing perceptions about unfolding and future developments. At the same time, scenarios can help to highlight and explain the implications and long-term consequences of current trends and choices that may lie ahead. In this case, it is particularly important that the scenarios are perceived to be credible, stimulating, thought provoking, and—most important—relevant to the audience (117). This approach combines two groups of scenarios suggested in the Millennium Ecosystem Assessment (118, 119)—new conversation scenarios (those aimed at exploring new and unknown topics that can be used as an educational tool for wide audiences, de facto offering a tool for collaborative learning exercises), and groups-in-conflict scenarios (those used to help understand differences in worldview and perceptions of groups, and to jointly explore consequences of actions).

Scenarios provide a platform for future discussions (120, 121). But after questions have been formulated, scenarios developed and analyzed, results interpreted, and implications discussed (whether in a single cycle or after multiple iterations), an effective foresight process should lead to (or at least inform) choices. Schoemaker (122) argues that the application of scenarios may help decision makers to overcome the usual errors they might make—such as overconfidence about future events or a tendency toward tunnel vision in the range of possible outcomes. Well-thought-out and developed scenarios provide more accurate and precise information about future outcomes. Furthermore, the incorporation of expert opinions and/or the most likely changes to critical parameters also help make scenario analysis a valuable tool for decision makers (26). The types of scenarios developed depend on the decision makers' objectives [e.g., emission mitigation scenarios (9) or conservation decisions (123)], offering both theoretical and empirical solutions (41).

The track record of the use of scenarios as a tool for policy guidance is diverse, fragmented, and often unclear, at least when multistakeholder, societal scenario processes are concerned (124). Often, a general understanding that uncertain futures around a certain domain should be explored leads to a scenario exercise—but if the organizers of a given process do not have a strong mandate or obligation to make the scenarios useful for a specific policy purpose, there is a high chance that too little thought and planning will be put into the integration of scenario development and policy formulation (125).

When scenario processes are directly commissioned by decision makers to investigate specific questions, the likelihood of their impact on policy increases, but careful design of the integration of scenario and policy formulation processes is still required (126). Furthermore, when scenario processes are designed to be integrated with policy formulation as a tool to test and develop more robust policies, such processes can be used to open up policy formulation to diverse societal actors who bring their own concerns and desires for the future to the table—both complicating and broadening the process. This makes scenario-guided policy formulation a unique opportunity for more participatory governance, but the design of stakeholder participation has to be considered carefully, and the process has to be open enough to allow participants to make real inputs to policy but also managed appropriately to keep it effective (127). Vervoort et al. (45) report on the need for continual engagement with policy makers to make sure all agree on how foresight should be used to guide policies, for instance to generate policy themes or to test detailed plans, what the best moments in a policy cycle are for scenario guidance, when wider participation is most useful, and which steps require more focused engagement by smaller groups of societal actors. The use of scenario guidance in policy formulation can then yield important insights into how to make a policy or plan more robust and inclusive. Even after these insights are generated, however, continued collaboration is necessary to ensure these alterations end up in final, accepted versions of policies and plans, and to track how policies translate to implementation.

4. RECENT EXAMPLES OF SCENARIO EXERCISES

Numerous examples of scenario and foresight studies have been mentioned in the previous sections. In this section, we briefly elaborate on several examples related to global environmental change, agriculture, food, and sustainable development that illustrate progress and challenges in using scenarios and foresight to address these critical areas.

4.1. Global Environmental Change

Scenarios have been used to assess the potential impact of climate change ever since the start of the IPCC in 1988, and all IPCC assessment reports contain a large section on scenarios, starting with the first one (128). One might argue that this was a logical extension of work done since the 1970s on the use of fossil fuels, in which scenario thinking was introduced. An article in the first issue of the journal *Climatic Change* notes that "[n]early all scenarios for future U.S. energy supply systems show heavy dependence on coal" (129, p. 45), and the oil company Shell has also used scenarios extensively (15, 27, 130, 131).

As noted in Section 3.3.4, the IPCC process has also led to the development of standardized climate and socioeconomic scenarios in the form of RCPs and SSPs, to facilitate analysis and comparison across multiple models and studies. These have been extensively used in climate change analysis (see Section 4.2), but discussion continues about how specific elements of the SSP narratives (e.g., land use, trade policy, and dietary preferences) are to be implemented in different models, and whether additional RCPs may be needed to expand the range below the existing set (to reflect the goal of the Paris Agreement to keep global warming well below 2°C), or to fill out the range at the upper end of the existing set (to capture a more likely pathway).

Following the IPCC work, scenario work has been applied in many global environmental assessments. The United Nations Environment Programme's (UNEP's) 2003 *Global Environmental Outlook* (GEO)-3 report was the first of these outlooks with a full scenario section, largely based on the IPCC scenario framework (132). Another important report on global environmental change containing a large scenarios component was the 2005 Millennium Ecosystem Assessment, which included four exploratory scenarios under the headings of "Global Orchestration," "Order from Strength," "Adaptive Mosaic," and "TechnoGarden" (118, 119). The scenarios explored key uncertainties about the degree of globalization versus regionalization in combination with the attitudes of decision makers at different levels toward environmental management. The scenarios were analyzed with respect to their implications for ecosystem services provision and human well-being outcomes across the globe. They were mainly intended to raise awareness; create space for in-depth discussion with stakeholders in government, industry, and civil society about long-term environmental change implications; create a joint understanding and sense of urgency about needed policy change; and stimulate the search for new solutions. The 2007 GEO-4 report contained a large scenario section with four contrasting scenarios that differentially prioritized markets, policy, security, and sustainability (133). In some of the more recent global reports, the emphasis has shifted from explorative scenario studies to a more solution-oriented approach. For example, the emphasis of the 2012 GEO-5 report was explicitly on choices and strategies that could lead to a sustainable future (134), the IPCC AR5 WG III report examines "mitigation pathways and measures in the context of sustainable development" (58), and the European Commission has drawn on scenarios to inform policy on global food security (135) as well as food safety and nutrition (136).

4.2. The Agricultural Model Intercomparison and Improvement Project

AgMIP is an international collaborative effort to improve simulation modeling tools to better understand the challenges facing agriculture and food security under climate change, and to explore options to address those challenges (137). Efforts focus on improving and linking climate models, crop models, and economic models at global and regional scales to inform policy dialog through forums such as the IPCC. For example, the AgMIP Global Economics Team consists of roughly a dozen modeling groups around the world (61), and explores the impacts of alternative combined socioeconomic (SSP) and climate (RCP) scenarios on yields, production, prices, and trade for major agricultural commodities.

A first round of analyses projected that climate change would reduce crop yields by a global average of 17% in 2050 relative to a scenario without climate change, but that these losses would be reduced to 11% after endogenous economic responses are considered (62, 138). A second round of analyses, exploring a wider range of socioeconomic and climate scenarios, projected somewhat smaller yield reductions, due in part to model improvements allowing greater flexibility in economic responses (81). In both cases, changes in total global production and consumption (to 2050) due to climate change are relatively small, but increases in harvested area and prices raise concerns about environmental impacts and food security, respectively. Ongoing work is exploring these issues in greater depth, at both global and regional scales (139).

4.3. Regional Scenarios of Climate Change, Agriculture, and Food Security

The CGIAR research program CCAFS supports a project that has focused on the creation of regional scenarios on climate change, food security, development, and environmental impacts in East and West Africa, South and Southeast Asia, the Andes, Central America, and the Pacific (45, 140). These scenarios have been created to explore future contexts for national policy making in several countries in each of these regions. The scenarios were originally created through driver analyses and narrative development by a wide range of regional stakeholders from policy, the private sector, civil society, the media, and academia in each region. The process evolved from a two-axes scenario development approach initially to a more multidimensional model in later regions to better respond to diverse policy interests (78). The scenarios were then quantified using multiple global agricultural economic models that offer comparable and complementary simulation results: the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), developed by the International Food Policy Research Institute (141–143), and the Global Biosphere Management Model (GLOBIOM), developed by the International Institute of Applied Systems Analysis (144). In some regions, additional models were used to create maps of land use or water use (145).

Scenario design took place in intensive regional consultations, followed by a careful process of quantification and analysis (66, 146). Even so, it is noteworthy that approximately 70% of this project's time has focused on the use of scenarios in each region for detailed policy formulation processes. Each such process takes one to two years of intense collaboration between government and research teams, as well as close involvement by other societal actors. Over the course of the policy formulation process, the regional CCAFS scenarios are adapted and customized to national policy contexts and used to stress-test and develop a policy or plan, with the aim to make it more robust and/or flexible to future uncertainties as well as more inclusive of the concerns and interests of a wide variety of societal actors. The combination of adapting existing regional scenarios for specific policy processes, and an intensive and long-term focus on guiding each individual policy process, has resulted in the formulation of major national plans and policies in the countries of the seven project regions (147).

The CGIAR Research Program on Policies, Institutions, and Markets also supports capacity development and foresight analysis to support decision making on agriculture, the environment, and food security through the Global Futures and Strategic Foresight initiative (**http://globalfutures.cgiar.org/**).

4.4. The Sustainable Development Goals

The Sustainable Development Goals agreed upon by nearly 200 countries in 2015, covering a wide spectrum from eradication of poverty and hunger to education and health, sustainable resource use, environmental protection, equity, and justice, represent the magnitude and complexity of the challenges the global community faces in the coming decades. Difficult as it was to articulate these goals and reach broad-based agreement, this was just the beginning. In a sense, the SDGs are the starting point for a grand normative scenario process, to figure out how these goals will be achieved. Various initiatives have already begun, including The World in 2050 (**http://www.iiasa.ac.at/web/home/research/twi/TWI2050.html**), which places these goals in the context of earlier work on planetary boundaries (148, 149). These will no doubt require concerted action through 2030 and beyond.

5. INSIGHTS AND RECOMMENDATIONS

The world faces increasingly complex challenges, and environment and resources play a critical part in most of them. Sustainably and equitably meeting rising demand for food and energy in the context of resource constraints and climate change are just a few examples. Because of the scale of these challenges—over space and time as well as social, economic, and political dimensions—outcomes are highly uncertain and will depend on the choices we make as well as how they interact with forces beyond our control. Systematic foresight involving scenario development and analysis will be essential to explore these uncertain futures in a way that can inform the choices we make.

Experience with formal foresight exercises dates back more than a century, including early applications in defense and business (particularly the energy sector). Environmental sciences have dominated published work in this area in more recent years, with extensive work currently under way in the areas of climate change, natural resources, agriculture, and food security. This experience highlights key questions. Given diverse and sometimes conflicting interests among stakeholders, how can foresight exercises be structured to ensure appropriate representation and participation? Given the complexity of biophysical and socioeconomic factors that characterize these challenges, are appropriate tools available to analyze the interactions involved? Given these questions, how can goals of participation and completeness be balanced against goals of transparency and simplicity?

Effective scenario planning is attributed to the combination of qualitative and quantitative approaches. The two can be highly complementary. But coupling qualitative and quantitative approaches is easier said than done, and despite existing efforts for improvement, disciplinary differences as well as institutional and cultural factors often segregate qualitative and quantitative teams, complicating the dialog and decision-making processes. Thus scenario exercises need to include carefully structured processes that provide a framework for the integration of different types of knowledge, including stakeholder expertise as well as scientific information, into the analysis.

Analysis of environmental and resource scenarios is further complicated because at all spatial and temporal scales there are complex and dynamic interactions between biophysical conditions (such as climate, biodiversity, and resource availability) and socioeconomic factors. Disadvantages include, among others, the complexity of such models, which require long time frames to be developed and tested, and potentially drive large uncertainties in their outcomes. Furthermore, new research is needed into different ways for coupling scenarios and scenario processes across scales to bring insights from one level into decision-making processes at other levels and enhance the usability of the exercises.

Interpreting and communicating the results of such complex models and processes also require careful attention. Quantitative output as calculated from a previous time step should be fed back into the scenario-building process to inform the narrative and the variables for the current time step; at the very least, qualitative narratives and quantitative trajectories should be compared in an iterative process. Ideally, a quantitative model would be able to run in a sufficiently short time so that it can provide rapid feedback, but this is rarely possible. Furthermore, it is rarely possible to prerun the model with all possible settings that might be of interest and generate a look-up table of precalculated output values. More typically, scenario processes must iterate multiple times between discrete quantitative and qualitative stages, implying large studies and long development times.

Despite these challenges and questions, experience from past and ongoing foresight exercises shows important progress and provides valuable insights. The long-standing use of war games in defense planning demonstrates the importance of direct participation by decision makers in interactive scenario exercises to enhance understanding of options and reach consensus. The IPCC process developed standardized scenarios for climate and socioeconomic change that are now widely used to analyze the impacts of climate change. The AgMIP network of climate, crop, and economic modelers uses these standardized scenarios and links their analysis across disciplines, modeling communities, and scales. The CCAFS regional scenario activities have facilitated dialog between diverse stakeholders at national and regional levels, and linked that dialog with quantitative modelers in an ongoing policy process. The Sustainable Development Goals in 2015 and the Paris Climate Accord in 2016 represent normative foresight challenges on a grand scale. Despite broad intergovernmental agreement and the tremendous stakes involved, achieving these goals will require sustained and systematic dialog and analysis in proportion. Lessons from previous foresight experiences will be essential.

SUMMARY POINTS

1. Increasingly complex environmental and resource challenges call for systematic foresight involving scenario development and analysis to inform choices.

2. Formal foresight exercises date back more than a century in defense and business applications, but environmental sciences now dominate published work in this area.
3. Qualitative and quantitative foresight approaches can be highly complementary, and a carefully structured combination of the two can facilitate engagement by diverse stakeholders, including decision makers and researchers from different disciplines, to enhance the relevance of scenarios and the credibility of results.
4. Improvements are being made in both qualitative and quantitative approaches, and coupled approaches are seen as the gold standard, but linking them quickly to inform real-time decision making remains difficult.
5. Frameworks for standardizing the use of scenarios in environmental assessment have been proposed, but as yet none have been adopted. The diversity of scenario methods used in environmental science makes it difficult to develop comparable platforms and data, and the level of standardization remains low compared with the financial sector.
6. Long experience with scenario exercises in defense planning indicates the importance of direct participation by decision makers (as well as researchers). Such participation is equally important in environmental and resource planning, but may be more difficult to implement given less hierarchical institutional contexts.

FUTURE ISSUES

1. To better inform decision making in environment and resources, methods for linking qualitative and quantitative information in scenario processes warrant new approaches and ideas to explore alternative futures that are credible and usable but also challenging and thought-provoking.
2. Further research is needed on ways to integrate knowledge across disciplinary boundaries and combine this with the expertise of diverse stakeholder groups to better address their specific decision-making contexts and questions.
3. Further research is needed on ways to link and compare scenario processes and information across geographical and temporal levels and scales.
4. Further research is needed on the uncertainties and confidence levels associated with scenario outcomes.
5. Continued improvement of quantitative models is needed to reduce the time required to feed results back into ongoing dialog processes.
6. Development of standard protocols would facilitate comparison across scenario exercises and building of a common database of results, but potentially at the cost of flexibility that is valuable for context-specific applications.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

K.W. acknowledges financial support from the CGIAR Research Program on Policies, Institutions, and Markets (PIM), the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), and the Bill and Melinda Gates Foundation. A.L. acknowledges funding from the Australian Research Council's DECRA Fellowship program (DE150100328). S.L., J.V., and N.B. acknowledge financial support from the EU FP7 project TRANSMANGO (theme KBBE.2013.2.5-01). We also thank the *Annual Review of Environment and Resources* Editorial Committee for feedback on our article.

LITERATURE CITED

1. Steffen W, Crutzen PJ, McNeill JR. 2007. The Anthropocene: Are humans now overwhelming the great forces of nature? *AMBIO* 36:614–21
2. Mervis J. 2017. Not so fast. *Science* 358:1371–74
3. Missirian A, Schlenker W. 2017. Asylum applications respond to temperature fluctuations. *Science* 358:1610–14
4. van Dijk M, Meijerink GW. 2014. A review of global food security scenario and assessment studies: results, gaps and research priorities. *Glob. Food Secur.* 3:227–38
5. Le Mouël C, Forslund A. 2017. How can we feed the world in 2050? A review of the responses from global scenario studies. *Eur. Rev. Agric. Econ.* 44:541–91
6. Zurek MB, Henrichs T. 2007. Linking scenarios across geographical scales in international environmental assessments. *Technol. Forecast. Soc. Change* 74:1282–95
7. Voros J. 2003. A generic foresight process framework. *Foresight* 5:10–21
8. Intergovernmental Panel on Climate Change (IPCC). 2007. *Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC
9. Börjeson L, Höjer M, Dreborg K-H, Ekvall T, Finnveden G. 2006. Scenario types and techniques: towards a user's guide. *Futures* 38:723–39
10. Davidson P. 1996. Reality and economic theory. *J. Post Keynes. Econ.* 18:479–508
11. Amer M, Daim TU, Jetter A. 2013. A review of scenario planning. *Futures* 46:23–40
12. Ramírez R, Selin C. 2014. Plausibility and probability in scenario planning. *Foresight* 16:54–74
13. Westhoek HJ, van den Berg M, Bakkes JA. 2006. Scenario development to explore the future of Europe's rural areas. *Agric. Ecosyst. Environ.* 114:7–20
14. van Notten PWF, Rotmans J, van Asselt MBA, Rothman DS. 2003. An updated scenario typology. *Futures* 35:423–43
15. Wack P. 1985. Scenarios: uncharted waters ahead. *Harvard Business Review*, Sept., pp. 73–89
16. Perla PP. 1990. *The Art of Wargaming: A Guide for Professionals and Hobbyists*. Annapolis, MD: Nav. Inst. Press
17. Hanley JT. 2017. Changing DoD's analysis paradigm. *Naval War Coll. Rev.* 70(1):64–103
18. Wisecup JV. 2010. President's forum. *Naval War Coll. Rev.* 63(4):19–23
19. Rubel RC. 2006. The epistemology of war gaming. *Naval War Coll. Rev.* 59(2):108–28
20. Watman K. 2003. War gaming and its role in examining the future. *Brown J. World Aff.* 10:51–61
21. Hanley JT Jr. 1991. *On Wargaming: A Critique of Strategic Operational Gaming*. PhD Thesis, Yale Univ.
22. Bennett B. 2012. Anatomy of a war game: training for nuclear war on the Korean Peninsula. *World Policy J.* 29:21–23
23. Dunnigan JF. 2003. War games, preemption, and other curious behavior. *Brown J. World Aff.* 10:77–86
24. Perla PP, McGrady E. 2011. Why wargaming works. *Naval War Coll. Rev.* 64(4):111–30
25. Wilkes BJ. 2001. Silver flag: a concept for operational warfare. *Air Space Power J.* 15:47–56
26. Bradfield R, Wright G, Burt G, Cairns G, Van Der Heijden K. 2005. The origins and evolution of scenario techniques in long range business planning. *Futures* 37:795–812
27. Wack P. 1985. Scenarios: shooting the rapids. How medium-term analysis illuminated the power of scenarios for shell management. *Harvard Business Review*, Novemb., pp. 139–50

28. Godet M, Durance P, Gerber A. 2008. *Strategic foresight: use and misuse of scenario building*. Work. Pap., Lab. Innov. Prospect. Stratég. Org., Paris
29. Martelli A. 2001. Scenario building and scenario planning: state of the art and prospects of evolution. *Futures Res. Q.* 17:57–74
30. Bain & Company. 2015. Scenario and contingency planning. *Insights*, Novemb. 7.
31. Rohrbeck R, Schwarz JO. 2013. The value contribution of strategic foresight: insights from an empirical study of large European companies. *Technol. Forecast. Soc. Change* 80:1593–606
32. Phelps R, Chan C, Kapsalis SC. 2001. Does scenario planning affect performance? Two exploratory studies. *J. Bus. Res.* 51:223–32
33. Visser MP, Chermack TJ. 2009. Perceptions of the relationship between scenario planning and firm performance: A qualitative study. *Futures* 41:581–92
34. Balarezo J, Nielsen BB. 2017. Scenario planning as organizational intervention: an integrative framework and future research directions. *Rev. Int. Bus. Strategy* 27:2–52
35. Höjer M, Ahlroth S, Dreborg K-H, Ekvall T, Finnveden G, et al. 2008. Scenarios in selected tools for environmental systems analysis. *J. Cleaner Prod.* 16:1958–70
36. Liu Y, Mahmoud M, Hartmann H, Stewart S, Wagener T, et al. 2008. Chapter Nine: Formal scenario development for environmental impact assessment studies. *Dev. Int. Environ. Assess.* 3:145–62
37. Institute of Environmental Management & Assessment (IMEA). 2011. *Special Report—The State of Environmental Impact Assessment Practice in the UK*. Lincoln, UK: IMEA
38. Maynard T. 2015. *Food System Shock: The Insurance Impacts of Acute Disruption to Global Food Supply*. London: Lloyd's
39. Popper R. 2009. *Mapping foresight: revealing how Europe and other world regions navigate into the future*. Eur. Foresight Monit. Netw. Rep. EUR 24041 EN, Publ. Off. EU, Luxembourg
40. Bishop P, Hines A, Collins T. 2007. The current state of scenario development: an overview of techniques. *Foresight* 9:5–25
41. Varum CA, Melo C. 2010. Directions in scenario planning literature—a review of the past decades. *Futures* 42:355–69
42. Wilson I. 2000. From scenario thinking to strategic action. *Technol. Forecast. Soc. Change* 65:23–29
43. Hennicke P. 2004. Scenarios for a robust policy mix: the final report of the German study commission on sustainable energy supply. *Energy Policy* 32:1673–78
44. Jäger J, Rounsevell MDA, Harrison PA, Omann I, Dunford R, et al. 2015. Assessing policy robustness of climate change adaptation measures across sectors and scenarios. *Clim. Change* 128:395–407
45. Vervoort JM, Thornton PK, Kristjanson P, Förch W, Ericksen PJ, et al. 2014. Challenges to scenario-guided adaptive action on food security under climate change. *Glob. Environ. Change* 28:383–94
46. Kaplan S, Garrick BJ. 1981. On the quantitative definition of risk. *Risk Anal.* 1:11–27
47. Pfister S, Bayer P, Koehler A, Hellweg S. 2011. Projected water consumption in future global agriculture: scenarios and related impacts. *Sci. Total Environ.* 409:4206–16
48. Swetnam RD, Fisher B, Mbilinyi BP, Munishi PKT, Willcock S, et al. 2011. Mapping socio-economic scenarios of land cover change: a GIS method to enable ecosystem service modelling. *J. Environ. Manag.* 92:563–74
49. Chen L, Messing I, Zhang S, Fu B, Ledin S. 2003. Land use evaluation and scenario analysis towards sustainable planning on the Loess Plateau in China—case study in a small catchment. *CATENA* 54:303–16
50. Bartolini F, Bazzani GM, Gallerani V, Raggi M, Viaggi D. 2007. The impact of water and agriculture policy scenarios on irrigated farming systems in Italy: an analysis based on farm level multi-attribute linear programming models. *Agric. Syst.* 93:90–114
51. Flachsbarth I, Willaarts B, Xie H, Pitois G, Ringler C, Garrido A. 2015. The role of Latin America's land and water resources for global food security: environmental trade-offs of future food production pathways. *PLOS ONE* 10(1): e0116733
52. Zanoli R, Gambelli D, Vairo D. 2012. Scenarios of the organic food market in Europe. *Food Policy* 37:41–57
53. Adams RM, McCarl BA, Mearns LO. 2003. The effects of spatial scale of climate scenarios on economic assessments: an example from U.S. agriculture. *Clim. Change* 60:131–48

54. Bock A-K, Lheureux K, Libeau-Dulos M, Nilsagård H, Rodriguez-Cerezo E. 2002. *Scenarios for co-existence of genetically modified, conventional and organic crops in European agriculture*. Joint Res. Cent. Rep. EUR 20394EN, Eur. Comm., Joint Res. Cent., Seville, Spain
55. Reilly M, Willenbockel D. 2010. Managing uncertainty: a review of food system scenario analysis and modelling. *Philos. Trans. R. Soc. B* 365:3049–63
56. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, et al. 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463:747
57. Nakicenovic N, Alcamo J, Grubler A, Riahi K, Roehrl R, et al. 2000. *Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press
58. Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge Univ. Press
59. Parry ML, Rosenzweig C, Iglesias A, Livermore M, Fischer G. 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Glob. Environ. Change* 14:53–67
60. Vermeulen S, Campbell BM, Ingram JS. 2012. Climate change and food systems. *Annu. Rev. Environ. Resourc.* 37:195–222
61. von Lampe M, Willenbockel D, Ahammad H, Blanc E, Cai Y, et al. 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agric. Econ.* 45:3–20
62. Nelson GC, van der Mensbrugghe D, Ahammad H, Blanc E, Calvin K, et al. 2014. Agriculture and climate change in global scenarios: Why don't the models agree. *Agric. Econ.* 45:85–101
63. Schlüter M, McAllister RRJ, Arlinghaus R, Bunnefeld N, Eisenack K, et al. 2012. New horizons for managing the environment: a review of coupled social-ecological systems modeling. *Nat. Resource Model.* 25:219–72
64. Ash N, Blanco H, Brown C, Garcia K, Tomich T, Vira B. 2010. *Ecosystems and Human Well-Being: A Manual for Assessment Practitioners*. Washington, DC: Island Press
65. Mason-D'Croz D, Vervoort J, Palazzo A, Islam S, Lord S, et al. 2016. Multi-factor, multi-state, multi-model scenarios: exploring food and climate futures for Southeast Asia. *Environ. Model. Softw.* 83:255–70
66. Palazzo A, Vervoort JM, Mason-D'Croz D, Rutting L, Havlík P, et al. 2017. Linking regional stakeholder scenarios and shared socioeconomic pathways: quantified West African food and climate futures in a global context. *Glob. Environ. Change* 45:227–42
67. Vervoort JM, Rutting L, Kok K, Hermans FLP, Veldkamp T, et al. 2012. Exploring dimensions, scales, and cross-scale dynamics from the perspectives of change agents in social-ecological systems. *Ecol. Soc.* 17:24
68. Gibson CC, Ostrom E, Ahn TK. 2000. The concept of scale and the human dimensions of global change: a survey. *Ecol. Econ.* 32:217–39
69. Cash D, Adger WN, Berkes F, Garden P, Lebel L, et al. 2006. Scale and cross-scale dynamics: governance and information in a multilevel world. *Ecol. Soc.* 11:8
70. Biggs R, Raudsepp-Hearne C, Atkinson-Palombo C, Bohensky E, Boyd E, et al. 2007. Linking futures across scales: a dialog on multiscale scenarios. *Ecol. Soc.* 12:17
71. Kok K, Biggs R, Zurek M. 2007. Methods for developing multiscale participatory scenarios: insights from Southern Africa and Europe. *Ecol. Soc.* 13:8
72. Bennett EM, Solan M, Biggs R, McPhearson T, Norström AV, et al. 2016. Bright spots: seeds of a good Anthropocene. *Front. Ecol. Environ.* 14:441–48
73. Kaplan S, Haimes YY, Garrick BJ. 2001. Fitting hierarchical holographic modeling into the theory of scenario structuring and a resulting refinement to the quantitative definition of risk. *Risk Anal.* 21:807–19
74. Aven T. 2011. On some recent definitions and analysis frameworks for risk, vulnerability, and resilience. *Risk Anal.* 31:515–22
75. Lempert RJ, Groves DJ, Popper SW, Bankes SC. 2006. A general, analytic method for generating robust strategies and narrative scenarios. *Manag. Sci.* 52:514–28
76. Bacon E. 2012. Writing Russia's future: paradigms, drivers, and scenarios. *Eur. Asia Stud.* 64:1165–89

77. Carlsen H, Eriksson EA, Dreborg KH, Johansson B, Bodin Ö. 2016. Systematic exploration of scenario spaces. *Foresight* 18:59–75
78. Lord S, Helfgott A, Vervoort JM. 2016. Choosing diverse sets of plausible scenarios in multidimensional exploratory futures techniques. *Futures* 77:11–27
79. Bryant BP, Lempert RJ. 2010. Thinking inside the box: a participatory, computer-assisted approach to scenario discovery. *Technol. Forecast. Soc. Change* 77:34–49
80. Carlsen H, Lempert R, Wikman-Svahn P, Schweizer V. 2016. Choosing small sets of policy-relevant scenarios by combining vulnerability and diversity approaches. *Environ. Model. Softw.* 84:155–64
81. Wiebe K, Lotze-Campen H, Sands R, Tabeau A, van der Mensbrugghe D, et al. 2015. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environ. Res. Lett.* 10:085010
82. Lord S, Nunes-Vaz R. 2013. Designing and evaluating layered security. *Int. J. Risk Assess. Manag.* 17:19–45
83. Heger T, Boman M. 2015. Networked foresight—the case of EIT ICT Labs. *Technol. Forecast. Soc. Change* 101:147–64
84. Rohrbeck R, Thom N, Arnold H. 2015. IT tools for foresight: the integrated insight and response system of Deutsche Telekom Innovation Laboratories. *Technol. Forecast. Soc. Change* 97:115–26
85. O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, et al. 2015. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* 42:169–80
86. O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, et al. 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* 122:387–400
87. Riahi K, Van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, et al. 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* 42:153–68
88. Skoglund J, Chen W. 2015. *Financial Risk Management: Applications in Market, Credit, Asset and Liability Management and Firmwide Risk*. Hoboken, NJ: Wiley
89. European Insurance and Occupational Pensions Authority (EIOPA). 2011. *EIOPA report on the Fifth Quantitative Impact Study (QIS5) for Solvency II*. Rep. EIOPA-TFQIS5-11/001, Eur. Ins. Occup. Pensions Author., Frankfurt
90. Alcamo J. 2001. *Scenarios as tools for international environmental assessments*. Environ. Issue Rep. 24, Eur. Environ. Agency, Copenhagen
91. Alcamo J. 2008. The SAS approach: combining qualitative and quantitative knowledge in environmental scenarios. In *Environmental Futures: The Practice of Environmental Scenario Analysis*, ed. J Alcamo, pp. 123–50. Amsterdam: Elsevier
92. Kemp-Benedict E. 2012. Telling better stories: strengthening the story in story and simulation. *Environ. Res. Lett.* 7:041004
93. Rounsevell MDA, Metzger MJ. 2010. Developing qualitative scenario storylines for environmental change assessment. *WIREs Clim. Change* 1:606–19
94. Wilkinson A, Kupers R. 2013. Living in the futures. *Harvard Business Review*, May. **https://hbr.org/2013/05/living-in-the-futures**
95. International Energy Agency (IEA). 2016. *World Energy Outlook 2016*. Paris: Org. Econ. Co-op. Dev. (OECD)/IEA
96. Haegeman K, Marinelli E, Scapolo F, Ricci A, Sokolov A. 2013. Quantitative and qualitative approaches in Future-oriented Technology Analysis (FTA): From combination to integration? *Technol. Forecast. Soc. Change* 80:386–97
97. Söderholm P, Hildingsson R, Johansson B, Khan J, Wilhelmsson F. 2011. Governing the transition to low-carbon futures: a critical survey of energy scenarios for 2050. *Futures* 43:1105–16
98. Mallampalli VR, Mavrommati G, Thompson J, Duveneck M, Meyer S, et al. 2016. Methods for translating narrative scenarios into quantitative assessments of land use change. *Environ. Model. Softw.* 82:7–20
99. Voinov A, Kolagani N, McCall MK, Glynn PD, Kragt ME, et al. 2016. Modelling with stakeholders—next generation. *Environ. Model. Softw.* 77:196–220

100. Hejazi M, Edmonds J, Clarke L, Kyle P, Davies E, et al. 2014. Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technol. Forecast. Soc. Change* 81:205–26
101. Gallopin GC, Hammond A, Raskin P, Swart R. 1997. *Branch Points: Global Scenarios and Human Choice*. Stockh., Sweden: Stockh. Environ. Inst.
102. Alcamo J, van Vuuren D, Rosegrant M, Alder J, Bennett E, et al. 2005. Methodology for developing the Millennium Ecosystem Assessment scenarios. See Ref. 118, pp. 145–72
103. Booth EG, Qiu J, Carpenter SR, Schatz J, Chen X, et al. 2016. From qualitative to quantitative environmental scenarios: translating storylines into biophysical modeling inputs at the watershed scale. *Environ. Model. Softw.* 85:80–97
104. Vervoort J, Helfgott A, Brzezina N, Moragues-Faus A, Lord S, et al. 2016. *Explorative EU Scenarios*. FP7 TRANSMANGO, Leuven, Belgium
105. Oksendal B, Sulem A. 2015. Applications of stochastic analysis. In *The Princeton Companion to Applied Mathematics*, ed. NJ Higham, MR Dennis, P Glendinning, PA Martin, S Santosa, J Tanner, pp. 319–27. Princeton, NJ: Princeton Univ. Press
106. Bala BK, Arshad FM, Noh KM. 2017. Scenario planning and modelling. In *System Dynamics: Modelling and Simulation*, ed. BK Bala, FM Arshad, KM Noh, pp. 149–62. Singapore: Springer
107. Nakajima Y, Yasui T, Ohkami Y, Kotake N. 2012. Modeling a policy for managing polio vaccine in Japan: scenario planning based on system dynamics. *Proc. 30th Intl. Conf. System Dynamics Society*, St. Gallen, Switzerland, July 22–26
108. van Vliet M, Kok K, Veldkamp T. 2010. Linking stakeholders and modellers in scenario studies: the use of Fuzzy Cognitive Maps as a communication and learning tool. *Futures* 42:1–14
109. Kok K. 2009. The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil. *Glob. Environ. Change* 19:122–33
110. Vennix JA. 1999. Group model-building: tackling messy problems. *Syst. Dyn. Rev.* 15:379–401
111. Hovmand PS. 2014. *Community Based System Dynamics*. Berlin: Springer
112. Nakajima Y, Yasui T, Ohkami Y, Kotake N. 2012. *Modeling a policy for managing polio vaccine in Japan: scenario planning based on system dynamics*. Presented at Int. Conf. Syst. Dyn. Soc., 30th, St. Gallen, Switz.
113. Acosta L, Klein RJT, Reidsma P, Metzger MJ, Rounsevell MDA, et al. 2013. A spatially explicit scenario-driven model of adaptive capacity to global change in Europe. *Glob. Environ. Change* 23:1211–24
114. Barton DN, Saloranta T, Moe SJ, Eggestad HO, Kuikka S. 2008. Bayesian belief networks as a meta-modelling tool in integrated river basin management—pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. *Ecol. Econ.* 66:91–104
115. Borsuk ME, Stow CA, Reckhow KH. 2004. A Bayesian network of eutrophication models for synthesis, prediction, and uncertainty analysis. *Ecol. Model.* 173:219–39
116. Pollino CA, Henderson C. 2010. *Bayesian Networks: A Guide for their Application in Natural Resources Management and Policy*. Canberra, Austr.: Landscape Logic
117. Alcamo J, Henrichs T. 2008. Towards guidelines for environmental scenario analysis. In *Environmental Futures: The Practice of Environmental Scenario Analysis*, ed. J Alcamo, pp. 13–35. Amsterdam: Elsevier
118. Carpenter SR, Pingali PL, Bennett EM, Zurek MB, eds. 2005. *Ecosystems and Human Well-Being: Scenarios.* Millen. Ecosys. Assess. Vol. 2. Washington, DC: Island Press
119. Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis*. Washington, DC: Island Press
120. Ringland G. 1998. *Scenario Planning: Managing for the Future*. Hoboken, NJ: Wiley
121. Ramirez R, Mukherjee M, Vezzoli S, Kramer AM. 2015. Scenarios as a scholarly methodology to produce "interesting research." *Futures* 71:70–87
122. Schoemaker PJ. 1995. Scenario planning: a tool for strategic thinking. *Sloan Manag. Rev.* 36:25–40
123. Peterson GD, Cumming GS, Carpenter SR. 2003. Scenario planning: a tool for conservation in an uncertain world. *Conserv. Biol.* 17:358–66
124. Bourgeois R, Ekboir J, Sette C, Egal C, Wongtchowsky M, Baltissen G. 2012. *The State of Foresight in Food and Agriculture and the Roads Toward Improvement*. Rome: Glob. Forum Agric. Res. Innov.
125. Pulver S, VanDeveer SD. 2009. "Thinking about tomorrows": scenarios, global environmental politics, and social science scholarship. *Glob. Environ. Polit.* 9:1–13

126. Jordan A, Turnpenny J. 2015. *The Tools of Policy Formulation: Actors, Capacities, Venues and Effects*. Cheltenham, UK: Edward Elgar Publ.
127. Chaudhury M, Vervoort J, Kristjanson P, Ericksen P, Ainslie A. 2013. Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. *Reg. Environ. Change* 13:389–98
128. Intergovernmental Panel on Climate Change (IPCC). 1990. *Emissions Scenarios Prepared by the Response Strategies Working Group of the Intergovernmental Panel on Climate Change: Report of the Expert Group on Emissions Scenarios*. Washington: Island Press
129. Rotty RM, Weinberg AM. 1977. How long is coal's future? *Clim. Change* 1:45–57
130. Shell International. 2001. *Energy Needs, Choices and Possibilities: Scenarios to 2050*. London: Glob. Bus. Environ., Shell Int.
131. Shell International. 2018. *Shell Scenarios. Sky: Meeting the Goals of the Paris Agreement.* London: Glob. Bus. Environ., Shell. Int.
132. Bakkes JA, Potting J. 2004. *The GEO-3 scenarios 2002–2032: quantification and analysis of environmental impacts*. Rep. UNEP/DEWA/RS.03–4, Rep. RIVM 402001022, United Nations Environ. Progr., Nat. Inst. Public Health Environ., Netherlands
133. United Nations Environment Programme (UNEP). 2007. *Global Environment Outlook 4: GEO-4. Environment for Development*. Nairobi: UNEP
134. United Nations Environment Programme (UNEP). 2012. *Global Environment Outlook: GEO-5. Environment for the Future We Want.* Nairobi: UNEP
135. Maggio A, Criekinge TV, Malingreau JP. 2015. *Global Food Security 2030: Assessing Trends with a View to Guiding Future EU Policies*. Luxembourg: Publ. Off. EU
136. Mylona K, Maragkoudakis P-A, Bock A-K, Wollgast J, Lauro-Caldeira S, Ulberth F. 2016. *Delivering on EU Food Safety and Nutrition in 2050—Future Challenges and Policy Preparedness*. Luxembourg: Publ. Off. EU
137. Rosenzweig C, Jones JW, Hatfield JL, Ruane AC, Boote KJ, et al. 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): protocols and pilot studies. *Agric. For. Meteorol.* 170:166–82
138. Nelson GC, Shively GE. 2014. Modeling climate change and agriculture: an introduction to the special issue. *Agric. Econ.* 45:1–2
139. Rosenzweig C, Ruane A, Antle J, Elliott J, Ashfaq M, et al. 2018. Coordinating AgMIP data and models across global and regional scales for 1.5°C and 2.0°C assessments. *Philos. Trans. R. Soc. A.* 376:20160455
140. Vermeulen SJ, Challinor AJ, Thornton PK, Campbell BM, Eriyagama N, et al. 2013. Addressing uncertainty in adaptation planning for agriculture. *PNAS* 110:8357–62
141. Rosegrant MW, Koo J, Cenacchi N, Ringler C, Robertson RD, et al. 2014. *Food Security in a World of Natural Resource Scarcity: The Role of Agricultural Technologies*. Washington, DC: Int. Food Policy Res. Inst.
142. Robinson S, Mason-D'Croz D, Sulser T, Islam S, Robertson R, et al. 2015. *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description for Version 3*. Washington, DC: Int. Food Policy Res. Inst.
143. Islam S, Cenacchi N, Sulser TB, Gbegbelegbe S, Hareau G, et al. 2016. Structural approaches to modeling the impact of climate change and adaptation technologies on crop yields and food security. *Glob. Food Secur.* 10:63–70
144. Valin H, Havlík P, Mosnier A, Herrero M, Schmid E, Obersteiner M. 2013. Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? *Environ. Res. Lett.* 8:035019
145. van Soesbergen A, Arnell AP, Sassen M, Stuch B, Schaldach R, et al. 2017. Exploring future agricultural development and biodiversity in Uganda, Rwanda and Burundi: a spatially explicit scenario-based assessment. *Regional Environ. Change* 17:1409–20
146. Mason-D'Croz D, Vervoort J, Palazzo A, Islam S, Lord S, et al. 2016. Multi-factor, multi-state, multi-model scenarios: exploring food and climate futures for Southeast Asia. *Environ. Model. Softw.* 83:255–70

147. Schubert C, Vervoort J. 2015. Future scenarios work informs climate and agriculture policies in seven countries. *CGIAR*, Sept. 7. **https://ccafs.cgiar.org/blog/future-scenarios-work-informs-climate-and-agriculture-policies-seven-countries#.WrzhmojwYVB**
148. Rockström J, Steffen W, Noone K, Persson Å, Chapin FS III, et al. 2009. A safe operating space for humanity. *Nature* 461:472–75
149. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, et al. 2015. Planetary boundaries: guiding human development on a changing planet. *Science* 347:1259855