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The problem of the future: sustainability science and scenario analysis

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Abstract

Unsustainable tendencies in the co-evolution of human and natural systems have stimulated a search for new approaches to understanding complex problems of environment and development. Recently, attention has been drawn to the emergence of a new "sustainability science", and core questions and research strategies have been proposed. A key challenge of sustainability is to examine the range of plausible future pathways of combined social and environmental systems under conditions of uncertainty, surprise, human choice and complexity. This requires charting new scientific territory and expanding the current global change research agenda. Scenario analysis—including new participatory and problem-oriented approaches—provides a powerful tool for integrating knowledge, scanning the future in an organized way and internalizing human choice into sustainability science.

1. Core questions

There is wide consensus in both science and policy that world development continues to move in an unsustainable direction. A recent comprehensive review of the state of the environment (UNEP, 2002) finds that, over the last 30 years, human and environmental circumstances have changed considerably and inequitably across the world. Social and environmental conditions have deteriorated in many places, and the integrity of life support systems has come under increasing threat.

Since the seminal report of the Brundtland Commission (WCED, 1987), the policy response has centered on a call for sustainable forms of development. While definitions of sustainable development vary widely (Robinson, 2002), most call attention to the need to maintain resilience in environmental and social systems by meeting a complex array of interacting environmental, social and economic conditions. One version of such an approach suggests three "imperatives" for sustainable development: the ecological (staying within biophysical carrying capacity), the social (providing systems of governance that propagate the values that people want to live by), and the economic (providing an adequate material standard of living for all) (Robinson and Tinker, 1998).

These concerns stimulated a scientific response, as new research initiatives addressed various biophysical aspects of global environmental change. In the 1980s, international global environmental change research was coordinated within the frameworks of the World Climate Research Programme (WCRP), the International Geosphere-Biosphere Programme (IGBP) and DIVERSITAS. As the importance of social and economic aspects increasingly became recognized, the International Human Dimensions Programme (IHDP) for the social sciences and humanities was formed in the 1990s. Global environmental change research matured into a broader agenda under the rubric of global change research. The interdependence of natural and social systems increasingly led to calls for interdisciplinary research efforts (e.g. Lubchenko, 1998; NAS, 1999; IGBP/IHDP/WCRP/Diversitas, 2001). In the context of IGBP, the global analysis, integration and modeling (GAIM) task force is advancing a framework for integrated research (Schellnhuber and Sahagian, 2002). For the 2002 World Summit on Sustainable Development, the world's scientific research programmes committed themselves to integrate societal problems into their endeavors (ICSU (International Council for Science), 2002).

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Box 1
Core questions for sustainability science

1. How can the dynamic interactions between nature and society—including lags and inertia—be better incorporated in emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?
2. How are long-term trends in environment and development, including consumption and population, reshaping nature-society interactions in ways relevant to sustainability?
3. What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?
4. Can scientifically meaningful "limits" or "boundaries" be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?
5. What systems of incentive structures—including markets, rules, norms and scientific information—can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
6. How can today's operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?
7. How can today's relatively independent activities of research planning, observation, assessment, and decision support be better integrated into systems for adaptive management and societal learning?
   Source: Kates et al. (2001).
8. How can the future be scanned in a creative, rigorous and policy-relevant manner that reflects the normative character of sustainability and incorporates different perspectives?"
   Source: this paper.

While the link between science-driven research activities and sustainability policy development remains weak (Cohen et al., 1998), the call to strengthen the contribution of science to a sustainability transition[1] has grown louder (Raven, 2002). Recently, Kates et al. (2001) identified a framework for an emerging "sustainability science" for generating useful knowledge to support a transition to sustainable development. Such a sustainability science would seek to illuminate the interactions between nature and society at different geographic scales from global to local. It would address the behavior of complex self-organizing systems and responses of the combined nature-society system to multiple and interacting stresses, involving different social actors. It would develop tools for monitoring key environmental and social conditions, and guidance on effective management systems.

The seven core questions proposed for sustainability science by Kates et al. (2001) are collected in Box 1. The emphasis is on understanding the systems complexities associated with sustainability, including the provision of information to help social actors to develop transition strategies. These core questions are a particular way of looking at the problem of sustainability, which reflects the scientific perspective it is intended to represent. Sustainability science is seen as fundamentally a problem of representing the interactions, behaviors and emergent properties of combined natural and social systems, and providing decision makers with better advice about the effects of various forms of behavior or intervention. These are indeed critical issues. Our goal here is to suggest ways in which scenario analysis can contribute to addressing them, and in so doing to help broaden the focus to encompass a richer set of considerations. These are derived in part from a "human science" perspective that emphasizes the need to develop approaches for evaluating future options, recognizing diverse epistemologies and problem definitions, and encompassing the deeply normative nature of the sustainability problem[2].

Where the questions in Box 1 touch upon the future, the proposed core questions focus on trends and discontinuities in those trends, and how these trends may be changed "in ways relevant to sustainability". However, they do not underscore the critical role of envisioning alternative futures, exploring plausible pathways, and identifying the factors conditioning long-term outcomes. To highlight some of these issues we have added an 8th question in Box 1: "How can the future be scanned in a creative, rigorous and policy-relevant manner that reflects the normative character of sustainability and incorporates different perspectives?"

The core questions outlined in Box 1 raise a number of research challenges for sustainability, which we discuss in the following section. We go on to summarize parallel developments in the use of scenario analysis to illuminate sustainability problems. We then argue that

[1] Detailed analysis of the integrated requirements for a sustainability transition was introduced by Raskin et al. (1998), and further developed by the National Research Council of the National Academy of Sciences of the United States (NAS, 1999), which spells out international targets for meeting human needs and preserving life support systems, as a basis for priorities both for research and action. Subsequently, on the policy side, the General Assembly of the United Nations adopted the Millennium Declaration (UNGA (United Nations General Assembly), 2000), which includes targets for a number of social and environmental sustainability problems.

[2] The scientific perspective described by the proposed core questions corresponds to the "descriptive" approach to the social sciences and humanities (Rayner and Malone, 1998), in which norms and values are not addressed explicitly. Our approach in this paper attempts to incorporate "normative" (explicitly accounting for the value-ladenness of the issues at stake and associated human goals) and "interpretive" (characterized by a focus on the meaning created by human agents in the conduct of social life) approaches.

scenario analysis is a natural and powerful tool for advancing important aspects of sustainability science, and close with some observations on future directions.

2. Research strategies

Kates et al. (2001) conclude that the structure, methods, and content of the scientific enterprise would have to change in order to pursue sustainability science adequately. From the core questions they derive four research strategies:

(i) *spanning multiple spatial scales* from local to global processes;
(ii) *accounting for temporal inertia and urgency* of problems that are both long-lived and perilous;
(iii) *reflecting functional complexity and multiple stresses* in human and environmental systems; and
(iv) *recognizing the wide range of outlooks* in order to generate knowledge usable for people with different perspectives.

These are important strategic challenges, indeed, which science has only begun to address. But others should be highlighted or, where implicit in the four generic strategies above, made explicit, in order to draw attention to the critical problem of the future (Core question 8). These are:

(v) *integrating across policy themes and issues* to capture the intricately linked ecological, social, economic, ethical and institutional dimensions of sustainability problems—adequately addressing any specific problems requires a framework that reflects the breadth and depth of interconnections (e.g., poverty, deforestation, climate change, land tenure systems, income distribution, trade regimes, etc., are co-determining);
(vi) *reflecting uncertainty: incorporating large uncertainties of very different kinds, surprise, critical thresholds and abrupt change* that are immanent in non-linear natural and social systems—the potential for and implications of novel events and rapid structural change beyond critical thresholds are fundamental to assess the resilience, vulnerability and suite of possible future states; understanding and reflecting large uncertainty in complex socio-ecological systems should be an explicit part of the sustainability science strategies;
(vii) *accounting for human volition* as a key conditioning factor of combined human and environmental systems—the constitution, reproduction and reformulation of human needs, wants and values is key to illuminating consumption, social goals, institutional innovation, social learning and the prospects for alternative futures;
(viii) *combining qualitative and quantitative analysis* to elevate non-quantifiable cultural, institutional and value aspects of the integrated system is required to avoid limiting the analysis to quantifiable aspects which are not necessarily the most crucial;[3] and
(ix) *making sustainability science more relevant to policy development and action through stakeholder participation*: the incorporation of the relevant values, perceptions and preferences of societal actors about the future into the research process is needed to encompass forms of knowledge normally not considered by analysts, and normative values.

3. Scenario analysis: history and current frontiers

Scanning these various research strategies for a new sustainability science, a recurrent theme is the challenge of integration. The systemic character of sustainability problems demands a holistic perspective that unifies across sectors, problems, methods, disciplines, spatial scales and time. Furthermore, the strict distinction between the realm of the normative and the objective, the "ought" and the "is", is not useful when the system under scrutiny entrains human values and choices as irreducible and critically important system constituents and drivers of change.

What are scenarios? In the context of sustainability science, integrated scenarios may be thought of as coherent and plausible stories, told in words and numbers, about the possible co-evolutionary pathways of combined human and environmental systems. They generally include a definition of problem boundaries, a characterization of current conditions and processes driving change, an identification of critical uncertainties and assumptions on how they are resolved, and images of the future. The characterization of the nature of human and environmental response under contrasting future conditions is key in scenario formulation. Reflecting respect for the uncertainty inherent in such systems, scenarios are neither predictions nor forecasts.

Scenario analysis is an evolving concept. The term has been applied to diverse efforts ranging from literary descriptions to model-based projections, from visionary thinking to minor adjustments to "business-as-usual" projections. Although scenario development as a systematic way of thinking about the future has a long

[3] Global change science continues to be dominated by quantitative approaches, whereas non-quantifiable factors, such as trust, power, emotional attachment and many others, which profoundly affect human behavior and the prospects for sustainability are left implicit or ignored.

history it has not been codified into a common set of definitions and procedures. Such methodological ambiguity is in many ways a source of strength for this evolving field of inquiry. The range of aims and the sheer complexity of the problem demand flexibility and creative exploration.

The broad use of the term "scenario" for characterizing the systematic framing of uncertain possibilities can be traced to post-World War II strategic studies. In particular, Kahn and Wiener (1967) explored possible consequences of nuclear proliferation, defining scenarios as "hypothetical sequences of events constructed with the purpose of focusing attention on causal processes and decision points". In the private sector, Shell has played a leading role since the 1970s developing scenarios to highlight world development possibilities that are relevant to the company's future, and to prepare company managers for responding to an uncertain future (Wack, 1985a, b), a process that has been used more widely in the business community since (Schwartz, 1991; Shell, 2002).

Systems modeling is another antecedent to contemporary scenario analysis. Mathematical simulations were used to forecast the behavior of the economy, its pressures on the environment, and resource constraints. A controversial early effort was *Limits to Growth* (Meadows et al., 1972) for the Club of Rome, which was followed with more complex modeling exercises (Mesarovic and Pestel, 1974). These studies found that trends in economy, demography and technology would overshoot the planet's carrying capacity in the 21st century, and explored the adjustments to growth necessary to avoid such a crisis. While calling attention to critical problems, the rigidity and uncertainty of the model specifications, and underestimation of society's adaptive capacity and of human ingenuity in the face of emerging problems has been used to discredit the work. In order to emphasize social and political aspects of development, particularly in developing countries, Herrera et al. (1976) developed the Latin American World Model to explore the requirements for a more egalitarian future. Häfele (1981) focused on long-term energy options in a finite world.

Another stream of scenario work focused on envisioning desirable futures, particularly in the energy field, in order to stimulate discussions on how to get there. Such "backcasting" studies (Robinson, 1982), mostly at the regional or national level, were conducted in dozens of countries, inspired by the early work of Lovins (1976, 1977) in developing scenarios of "soft energy paths". More recently, this backcasting approach has been applied in the context of sustainable futures, at both the regional and global scales (e.g. Robinson et al., 1996; Raskin et al., 1998, 2002).

After the Brundtland Report (WCED, 1987) and the 1992 Rio World Conference on Environment and Development, a second "wave" of global scenarios was launched in the context of the sustainability challenge. Some were model-based, and focusing on one issue such as climate change (Rotmans, 1990, Rotmans et al., 1994), but also broader efforts were undertaken, such as the updated work of Meadows et al. (1992) and new integrated studies on such themes as climate change, water scarcity, public health, and land-use (Rotmans and de Vries, 1997). The IPCC series of greenhouse gas emissions scenarios studies became successively more sophisticated (IPCC (Intergovernmental Panel on Climate Change), 1990; Leggett et al, 1992; Nakicenovic and Swart, 2000). Meanwhile, a number of studies adopted the narrative scenario tradition (e.g., Svedin and Aniansson, 1987).[4]

The distinction between *quantitative* (modeling) and *qualitative* (narrative) traditions of scenario analysis should be underscored. Quantitative analysis often relies on formal models, using mathematical algorithms and relationships to represent key features of human and environmental systems. Quantitative modeling is often used for predictive analysis, which is appropriate for simulating well-understood systems over sufficiently short times. But as complexity increases and the time horizon of interest lengthens, the power of prediction diminishes. Quantitative forecasting is legitimate to the degree the state of the system under consideration can be specified, the dynamics governing change are understood and known to be persistent, and mathematical algorithms can be created that map these relationships with sufficient accuracy for simulation. These conditions are violated when the task is to assess the long-range future of socio-ecological systems—state descriptions are uncertain, causal interactions are poorly understood and non-quantifiable factors are significant. In such case, even probabilistic forecasting of a given future state, or a spectrum of possible states, is not feasible. Systems can branch into multiple future pathways, each consistent with current conditions, trends and drivers, and some entailing discontinuous and novel behavior. This suggests the desirability of non-predictive forms of quantitative scenario analysis.

The limitations of quantitative analysis mean that it should be complemented by qualitative scenario exploration, which can probably better capture other factors influencing the future such as system shifts and surprises, or non-quantifiable issues such as values, cultural shifts and institutional features. The scenario narrative gives voice to the important qualitative factors shaping development such as values, behaviors and institutions, providing a broader perspective than is

[4] For a recent review of both modeling and narrative global scenarios analyses, mainly related to climate change, see Morita et al. (2001) and for an overview of applications of scenarios for climate change impacts, see Carter et al. (2001).

possible from mathematical modeling alone. Recent combinations of long-term narratives with scenarios quantification are attempting to combine the advantages of both approaches (Raskin et al., 1998; Nakicenovic and Swart, 2000, Tansey et al., 2002). Narrative offers texture, richness and insight, while quantitative analysis offers structure, discipline and rigor. In this sense, scenario analysis, with its rich history of alternative traditions and approaches, offers the potential of fostering the integration of descriptive and normative or interpretive traditions. The art is in the balance (Raskin et al., 1996).

Another way of distinguishing between types of scenarios is between primarily *descriptive* scenarios, i.e., scenarios describing possible developments starting from what we know about current conditions and trends, and primarily *normative* scenarios, i.e., scenarios which are constructed to lead to a future that is afforded a specific subjective value by the scenario authors. We add the word "primarily" because in practice scenarios have elements of both types, but with great differences in emphasis. Neither of these types is value-free, since both embody extra-scientific judgments about how the problem is to be framed, and what are reasonable or feasible assumptions. However, they differ in terms of overall purpose. That is, the choice between descriptive or normative scenarios is dependent on the objectives of the scenario development exercise. Normative scenarios represent organized attempts at evaluating the feasibility and consequences of trying to achieve certain desired outcomes or avoid the risks of undesirable ones. Descriptive scenario analysis, on the other hand, tries to articulate different plausible future societal developments, and explore their consequences.

From a methodological point of view, scenario authors can attempt to discern the likely outcome of a range of "expected" trends,[5] outline the implications of different assumptions not chosen on the basis of likelihood (*what-if analysis*) or examine the feasibility and implications of desirable futures—or risks of undesirable ones (*backcasting*). For sustainability problems, a combination of backcasting from an array of possible end-states and forward-looking analysis from initial conditions and drivers of change is appropriate. The latter helps to identify long-term risks and to specify sustainability conditions, while the former identifies the bandwidth of initial trajectories and available actions to "bend the curve" (Raskin et al., 1998) toward long-term sustainability goals.

[5] This does not imply that scenarios can be ("single") forecasts, or represent "most likely" or "business-as-usual". Such terms misleadingly suggest that the probability of particular futures is objectively known.

4. Integrating scenario analysis into the sustainability science toolkit

With this background, the potential for scenario analysis as a tool for addressing the core questions and methodological challenges of sustainability science comes into focus. Sustainability science must consider the interplay and dynamic evolution of social, economic and natural systems—it requires an *integrated and long-term perspective.* It must address the sustainability process as tentative, open and iterative, involving scientific, policy and public participation. It must capture the possibility of structural discontinuity and surprise in socio-ecological systems. And it must recognize the critical importance of alternative, and sometimes competing, stories, beliefs, institutional contexts and social structures.

Modern scenario methods are well-suited to these tasks. They can help to organize scientific insight into an integrated framework, gauge emerging risks, and challenge the imagination. They can provide a means for integration of descriptive and narrative elements, and qualitative and quantitative information. They ease communication with non-scientific audiences, and can engage diverse stakeholders as actors in scenario design and refinement. Though their subject is the future, scenarios can catalyze and guide appropriate action today for a sustainability transition.

Table 1 summarizes how scenario analysis can contribute to the various strategies introduced in the previous section. Several examples of recent projects demonstrate that various of the strategic challenges discussed above can be successfully met by scenario development and analysis. The work of the Global Scenario Group (Gallopin et al., 2001; Raskin et al., 1998, 2002; see http://www.gsg.org) not only couples regional to global scales, it also demonstrates how narratives can be successfully combined with model-based quantification of socio-economic developments and the environmental changes they cause. Their regional elaboration by UNEPs Global Environmental Outlook (UNEP, 2002) added a participatory regional consultative process and a direct link with policy processes. In the Netherlands, a series of projects have adopted a participatory scenario approach to analyze climate change response options. Initially, a project was implemented in which an integrated assessment model was used as the basis for a dialogue with negotiators of the UN Framework Convention on Climate Change (Klabbers et al., 1996; van Daalen et al., 1999), from which various interactive tools addressing specific questions developed (e.g. Swart et al., 1998; Berk and Janssen, 1997). The Climate OptiOns for the Long-term (COOL) project followed-up this work linking three spatial levels: national, European and global, and involving a variety of stakeholders such as national

Table 1
How can scenario analysis contribute to the methodological challenges of sustainability science

Research challenges		Key aspects	Contribution of scenario analysis
1.	Spanning spatial scales	Socio-ecological change must be studied at various levels of spatial resolution. Planetary, regional and local change are co-determining, but the linkages are not well understood.	Absent full scientific understanding of cross-scale linkages, "what-if" analysis can explore possible linkages and link local, regional and global perspectives in a common and consistent framework. Examples of regional scenarios associated with global scenarios are the GBFP, GSG and GEO projects (see main text).
2.	Accounting for temporal inertia and urgency	Processes play out at disparate time scales. System inertia characterizes both natural and socio-economic systems, while system change is increasingly indeterminate as the time horizon of analysis lengthens. Yet, societal decisions in response to long-term changes must be made in the short term.	Through backcasting, scenario analysis can link long-term goals (e.g., associated with a sustainability transition) to the shorter time horizon of today's decision makers. Examples are the tolerable windows/safe landing approaches to climate change, the GSGs "bending the curve" scenarios and the GBFP scenarios.
3.	Recognizing the wide range of outlooks	Sustainability science cannot be divorced from the values that shape people's perspectives and preferences with respect to sustainable futures and on ways and means to get there. Traditional scientific research is poorly equipped to deal with such normative issues.	Participatory scenario development, involving key stakeholders, is one of the ways to address different views on how the world works, how a sustainability transition could be envisaged and how it could be achieved. The GBFP and IPCC work are good examples.
4.	Reflecting functional complexity and multiple stresses	Multiple stresses affect the interdependent functioning social and environmental systems at all scales affecting their resilience. Scientific explanation of these complex interactions is likely to remain limited.	Qualitative expert knowledge applied in "what-if" scenario analysis can help charting possible complex linkages and multiple stresses, minimizing inconsistencies.
5.	Integrating across themes and issues	Component aspects and features of combined human and environmental systems are highly interdependent while policy interventions ripple and cascade through the combined system.	The scientific research and policy communities are both highly segregated into individual disciplines, subject areas, or themes. Integrated scenario analysis provides opportunities to broaden perspectives and reveal links. The GBFP, GSG and GEO projects are examples (see main text).
6.	Reflecting uncertainties, incorporating surprise, critical thresholds and abrupt change	Conventional methods are not well-equipped to deal with discontinuous changes in complex, non-linear systems. Scientific uncertainties in the complex socio-natural system relevant to sustainability issues are deep and may not be resolved. It is crucial to understand their importance and to make them explicit in research output.	Since surprises, critical thresholds and abrupt changes can have dramatic consequences for nature and society, creative, "what-if" scenarios offers the possibility of exploring the possibilities and analyzing the consequences. Svedin and Aniansson (1987) analyzed some options.
7.	Accounting for volition	The dynamics of change is influenced by individual and collective human decisions at all scales. Human behaviors and choice will determine both the goals and pathways of development and, hence, the prospects for a sustainability transition.	Scenario analysis is a powerful method to explore normatively distinct future images and alternative pathways for getting to each. It also helps researchers and users of scenarios alike to reflect on their own worldviews, biases and values, and thus enrich the science and practice of sustainability. The backcasting analyses of the COOL and the GBFP projects are examples.
8.	Combining qualitative and quantitative analysis	Cultural, institutional and value aspects of sustainability, although difficult to quantify, must be considered in a unified framework with those bio-physical, economic and social features in which quantitative analysis adds insight.	Narrative scenarios capture qualitative features, which can be used in conjunction with quantitative descriptions. The work from the Global Scenario Group and the IPCC are examples of this integration. Models can also be designed to capture qualitative aspects of scenario analysis, as in the QUEST model used in the GBFP.
9.	Engaging stakeholders	Human agents are an important internal feature of the system that sustainability science must address. Stakeholder engagement allows for taking into account the normative dimensions of sustainability, widens the knowledge base, and enhances mutual learning.	Scenarios promote communication between researchers and stakeholders, provide a structured framework for incorporating feedback into iterative analysis and offer a laboratory for testing (and influencing) human perceptions and goals.

climate negotiators; sectoral policy-makers; representatives of the private sector; representatives of environmental NGOs, politicians and government policy makers; and scientists (Berk et al., 2002). The main objective was to develop a process in which the implications of long-term sustainability goals related to climate change and equity were tied to short-term decision-making, using backcasting techniques. In the Georgia Basin Futures Project (GBFP) sustainable development scenarios in the Georgia Basin (on the west coast of the Canadian province of British Colombia) are explored in a ''second order'' backcasting framework (Robinson, 2003) by emphasizing community engagement through participatory integrated assessment methods (Tansey et al., 2002; see also www.basinfutures.net). The project addresses the challenges of linking between temporal and spatial scales, combining qualitative and quantitative scenario analysis, recognizing diverse outlooks and the influence of human choice, and linking with policy choices through stakeholder involvement. The Intergovernmental Panel on Climate Change (IPCC) has developed and used emissions scenarios for all three of its major assessments to date (IPCC, 1990; Leggett et al., 1992; Nakicenovic and Swart, 2000). The evolution of these scenario sets illustrates some of the challenges discussed in this paper. One business-as-usual scenario with three policy scenarios was conceived by a very limited number of modelers in relative isolation in the first assessment report (IPCC, 1990). In the second assessment a broader set of future scenarios were explored by the same small group, simply reflecting low, medium or high levels of development (Leggett et al., 1992). For its 3rd assessment, IPCC engaged a much wider set of experts and stakeholders to develop a much richer array of possible future developments, quantifying these with the help of a multitude of different modeling techniques and placing greenhouse gas emissions in the much broader context of socio-economic futures (Nakicenovic and Swart, 2000).

While scenario analysis cannot provide, of course, all the answers to the questions posed by sustainability science, it has an important role to play in synthesis, thinking about the future, and linking to policy and stakeholder communities. This role is complementary to the daunting amount of non-scenario work required for a robust sustainability science. Each type of scenario analysis can address different elements of the questions, and different challenges posed by the proposed research strategies. For example, backcasting approaches are useful when it comes to analyzing today's implications of long-term risks or long-term sustainability objectives, taking into account the inertia of natural and social systems, and for exploring different strategies. ''What-if'' analysis can be useful to evaluate under which conditions and when particular types of surprises could occur or thresholds be passed, and then to explore how to take these into account in today's decision-making processes. Forward-looking analysis is the appropriate methodology if we want to explore how different plausible socio-economic trends would work out in the short-term future and how these might interact with changes in natural systems, taking into account all relevant scientific uncertainties. Narrative scenario analysis facilitates a debate about normative aspects of sustainability, quantitative analysis can contribute to an adequate knowledge base and structural consistency.

Two aspects of scenario analysis in the context of a sustainability transition deserve special attention. First, scenario analysis for sustainability science as we see it goes beyond the traditional view on the relationship between science and policy, which assumes that science provides—sometimes on request, sometimes not—information to policy-makers in order to improve the quality of the decision-making process. Because of the apparent objective nature of scenarios developed from this perspective, they can be used by policy makers as a means of legitimizing rather than informing policy decisions.

Second, scenario analysis in the context of sustainability science has a potentially important role to play with regard to the increasing demand for more public and stakeholder involvement in the scientific activities, driven by a complex mix of factors, including increased public distrust of expert-driven decision making, growing awareness of a diversity of opinions in the scientific community, and increased sophistication of NGO, private sector and public involvement in regulatory and other decision-making fora. These evolving dimensions of the policy–science interface suggest that participatory forms of scenario analysis could be particularly effective in addressing the strategic and normative elements of the sustainability questions by incorporating values and preferences into the scenario analysis process itself. The objectives and design of a participatory scenario development exercise would be different for involvement of key stakeholders with advanced levels of scientific and technical expertise, as compared to engagement of the general public. But in all cases, scenario analysis for sustainability science should encompass mutual learning about the knowledge, positions and preferences of those involved, hopefully leading to better informed decision-making.[6]

[6] When combined in the exploration of desired futures, these two factors can give rise to a 'second order' form of backcasting, in which the desired future is an emergent property of the (participatory) process of creating and evaluating scenarios (Robinson, 2003). Such processes can combine the descriptive and normative approaches described earlier.

5. Conclusions and future directions

In summary, the emergence of a globalized phase of development is bringing both new opportunities and new perils. In many regions technological advances thrive, incomes increase, and health conditions improve. At the same time, poverty and hunger continue to plague hundreds of millions of people, conflicts abound, and ecological resources are under continuous pressure around the globe. With the possibility of the world's population doubling in this century and economic output increasing significantly, these problems can be expected to become even more pronounced and urgent. There is broad international agreement that a transition to sustainability is needed. But incomplete understanding of the problems, their causes and possible solutions makes society poorly prepared for such a transition. Moreover, the prospects for effective responses are complicated by contradictory philosophical views underlying policy and scientific discussions, views that are rarely made explicit, on how natural and human systems operate and interact, or how they should be managed.

Science can contribute to the sustainability transition by providing knowledge and guidance for navigating the journey from unsustainable contemporary patterns to a sustainable future. We have argued that scenario analysis offers one promising approach for operationalizing and enriching the required "sustainability science". The process and product of scenario analysis are equally important. In many contexts, scenario exercises will benefit by having both science and affected actors shape the analysis. Scientists bring knowledge of relevant processes and their linkages to the discourse and stakeholders enrich scenarios by bringing the perspectives of the human participants in the story of the future.

Scenario analysis can play a major role in addressing the challenges of sustainability science, especially the core question of how to scan the future in a structured, integrated and policy-relevant manner. Based on our scenario experiences over the past 20 years, we offer the following principles of good practice for those who would like to pursue scenario analysis as a means of addressing the vital questions of sustainability science. While each scenario exercise should be tailored to the specific problems and context, the following broad aspects should be considered:

- *A sufficiently large and diverse group of participants*: The typical size of the core group developing the scenarios in the examples cited earlier was between 10 and 40, usually involving experts from different disciplinary backgrounds and stakeholders with different interests. Interestingly, scientists, representatives from the private sector, governments and NGOs can find common ground through a scenario development process, since all these groups have usually had at least some exposure to scenarios, many even actively. Key stakeholders can be integrated directly into the problem definition, research design and scenario generation components of the research. For global scenario work, balanced representation from all regions is important and, ideally, a wider community of experts and stakeholders should be consulted, e.g., through consultations or review processes. The process of scenario development should be a process of mutual learning, and co-production of knowledge by those involved.
- *Adequate time for problem definition, knowledge base development, iterative scenario analysis, review and outreach*: It is vital to devote sufficient time and effort to build trust among team members and a shared appreciation of critical questions, the research strategy, and the audience. Over a period of months, storylines, possibly supported by quantification of key scenario elements, are best developed through several iterations, with penultimate results reviewed by peers beyond the core team. In many cases, the processes of interacting with stakeholders in the course of generating scenarios are as important as the scenario analysis itself. Finally, effective communication with the external audience needs careful attention, often requiring specialized skills and creative approaches beyond conventional scientific reports.
- *Full account of available scientific knowledge and rigor of methods*: All relevant scientific knowledge about what is known, and what is unknown about the problem being considered, should be incorporated into the scenario process. Existing scenario analyses, modeling exercises and databases can be useful sources of information and, in some cases, pitfalls to be avoided. This includes predetermined elements and critical uncertainties. Care should be taken when applying tools developed for one type of question for addressing other questions.
- *An explicit discussion about normative scenario elements*: Scenario analysis is a means to address the inherently normative dimensions of sustainability that takes sustainability science beyond the boundaries of the traditional scientific enterprise. The normative aspect enters the scenario in two ways. First, the storylines make assumptions about future behaviors and worldviews of scenario actors, involving assumptions on religion, spirituality, norms and values, as well as socio-political and institutional design questions. Second, the worldviews of the people creating the scenarios shape the way the story is told and what policy lessons are drawn. Transparency and rigor require that each of these normative dimensions be made explicit in developing

and analyzing the scenarios. Through open internal discussions and well-designed external communication, mental maps of both participants and audience can be revealed, challenged and enriched.

- *The development of coherent, engaging stories about the future*: While quantitative analysis can add insight and consistency, the power of scenarios lies in telling compelling stories that capture the imagination, understanding, and beliefs, hopes and dreams of participants. The stories should have a consistent logic and take into account evolving positions and power balance of stakeholders.

The narratives help reveal and address critical questions that might otherwise be neglected and offer a powerful vehicle for effective communication with target audiences.

- *Explore the possibility of surprise events and address possible seeds of change*: Many scenarios are quite narrow, restricting their analysis to dominant trends and incremental variations. The future however, can be influenced by surprise events and novel phenomena. Explicitly considering such possibilities will enrich the scenarios discussion and ultimate narratives. Similarly, "seeds of change" should be probed, societal or natural developments with the potential to significantly change society, and that are presently dormant or in their early stages of evolution (van Notten, 2002).
- *Place the focal problem in a broader context*: Often, scenario exercises focus on a single dimension of sustainability, such as climate change, biological diversity, poverty, International security, demographics, water, agriculture and energy. These issues, which become manifest at different spatial resolutions and time scales, influence each other. A systemic and integrated perspective will help real key linkages that influence the focal problem.

The development of an effective science of sustainability is an urgent endeavor that requires further clarification of the contours of its key questions and research agenda. The character of the sustainability problems compels a systemic exploration of the future, that is, sensitive to normative issues grounded in cultural, spiritual and philosophical attitudes of people, while incorporating methodological rigor. To succeed, sustainability science will need to be a dynamic, evolving field of inquiry and application, which seeks integration across disparate natural and social science perspectives. Scenario analysis offers a powerful platform for evolving an integrative, conceptually rich and inclusive process of relevant knowledge generation for a sustainable future.

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