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ABSTRACT

This paper reviews the latest research on scenarios including the processes and products for socio-environmental systems (SES) analysis, modeling and decision making. A group of scenario researchers and practitioners participated in a workshop to discuss consolidation of existing research on the development and use of scenario analysis in exploring and understanding the interplay between human and environmental systems. This paper presents an extended overview of the workshop discussions and follow-up review work. It is structured around the essential challenges that are crucial to progress support of decision making and learning with respect to our highly uncertain socio-environmental futures. It identifies a practical research agenda where challenges are grouped according to the process stage at which they are most significant: before, during, and after the creation of the scenarios as products. These challenges for SES include: enhancing the role of stakeholder and public engagement in the co-development of scenarios, linking scenarios across multiple geographical, sectoral and temporal scales, improving the links between the qualitative and quantitative aspects of scenario analysis, addressing uncertainties especially surprise, addressing scenario diversity and their consistency together, communicating scenarios including visualization methods, and linking scenarios to decision making.

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1. Introduction

Recently, Elsworth et al. (2020) identified a list of eight grand challenges in the modeling of socio-environmental systems (SES). These included ways forward to deal with multi-faceted uncertainty issues, scaling challenges, the combining of qualitative and quantitative methods, and capturing structural changes in SES models. This paper drills further into these types of challenges in SES modeling from the perspective of scenario and foresighting methods, recognising these processes can be especially valuable for thinking about our futures and dealing with pervasive uncertainties.

Scenario analysis has a long history in exploring our socio-environmental future, one which is plagued by uncertainties with respect to upcoming influences and the complexity of representing interactions in SES between humans and the environment (see e.g. Rothman, 2008; Hamilton et al., 2015; Maier et al., 2016; Guivarch et al., 2017; Elsworth et al., 2020). Being a foresighting approach, scenario analysis is based on the notion that the future, while inherently uncertain (or open), is not entirely unknowable; nor is it totally out of our control. Scenario analysis of an SES is not about predicting the future, but rather exploring and comparing a comprehensive range of diverse, plausible and conceivable futures, where these reflect both the state of the world at some point in the future and the pathways by which we move from the present day to those future times (Börjeson et al., 2006). These can include worlds that range from straightforward extrapolations of current trends (sometimes referred to as business as usual or reference scenarios) to more extreme possibilities, which reflect significant trend breaks or shocks. Although specific scenario methods may differ, the overall framework for many exercises combines qualitative and quantitative elements and therefore, implicitly or explicitly, shares a set of common characteristics with the story-and-simulation (SAS) approach (Alcamo, 2001; Alcamo, 2008). The SAS approach has been adopted in a number of scenario exercises, addressing complex and strategic issues such as climate change (e.g. Nakicenovic et al., 2000), energy (Trutnevyte et al., 2014), the water-energy nexus (e.g. Ackerman and Fisher, 2013), and rural development (e.g. Kok and Van Delden, 2009).

Scenario analysis expands our capacity to think and deal with the future by:

- exploring to what extent our choices today can shape the future and to what extent we will need to adapt to those parts of the future that we do not shape;
- promoting an informed discussion among stakeholders about the future;
- analysing various conditions causing vulnerabilities and opportunities for possible scenarios;

- focusing on formulating policies that are robust and/or flexible under different scenarios;
- challenging our assumptions about how the future may unfold; and
- raising awareness and public education about the need for proactiveness and foresight in dealing with our environmental challenges.

It has been long recognized that research methods around futures, such as scenario analysis, have a crucial role to play in generating better socio-environmental decisions and policies. However, the links between scenario analysis and decision making (i.e. societal, industry, policy) are still weak and not fully utilized, especially in dealing with complex societal issues (Van der Steen and Van Twist, 2013; van Dorsser et al., 2018), such as meeting the UN Sustainable Development Goals (United Nations, 2015) and transforming industries to cope with future changes. The mismatch between scenario analysis and decision making can be attributed to the limited capacity of existing approaches and methods to deal with the evolving and complex foresighting needs of society and policy.

As a first essential step for improving the link between scenario analysis and decisions, this paper takes an inward look at the state of the art on scenario use for socio-environmental systems analysis with the intent of identifying research gaps to strengthen the research and practice of scenario analysis for supporting decision making. Our inquiry focuses on the core challenges facing most scenario exercises that relate to both the process of scenario development and use, and the products themselves, i.e., the scenarios (Hulme and Dessai, 2008). These challenges require a research agenda that includes: enhancing the role of stakeholder and public engagement in the co-development of scenarios, linking scenarios across multiple geographical and temporal scales, addressing surprise, communicating scenarios, and linking scenarios to decision making.

By identifying core challenges, reviewing existing developments, and exposing research gaps around scenario analysis in socio-environmental system problems, we aim to consolidate existing knowledge to motivate and orient future scenario analysis efforts so that they play a stronger role in meeting societal and policy foresighting needs. While much of the scenario literature focuses on the steps involved in the actual construction of scenarios (e.g. defining topic/scope, identifying and analysing key factors/drivers, to characterizing and elaborating scenarios) (Amer et al., 2013; Huss and Honton, 1987), this present study examines scenario processes from a working/operational perspective. In implementing scenario processes in a real project, considerations such as who to involve and how do we work with diverse groups etc., come into play. This study therefore intends to provide guidance that will assist in the practice of scenario processes.

1.1. Research objective and questions

This synthesis paper attempts to consolidate the body of knowledge around scenario analysis and use by providing an overview of the state of the art and identifying remaining knowledge gaps to address the key challenges in scenario development and use. Whereas many of the challenges are relevant to any problem context, we consider these challenges from the position of developing and using scenarios for socio-environmental systems analysis. To the best of our knowledge, this is the first attempt to consolidate knowledge around the research challenges in this area. The paper takes a descriptive synthesis approach designed to gather and consolidate information about existing knowledge and future research needs. The following research questions serve as the basis of this synthesis effort: *What is the state of the art in scenario development and use for socio-environmental systems analysis? What are the key challenges and how are they being addressed? And what remains to be accomplished?* To answer these research questions, we focus on: (1) identifying and defining the challenges that researchers and practitioners face throughout the processes of scenario development and use (i.e. before, during, and after the creation of the scenarios as akin to the phases of modeling in [Badham et al., 2019](#)); (2) reviewing developments directed at addressing these questions; and (3) pointing to remaining knowledge gaps and areas for future research.

The paper also aims to provide a starting point for researchers and practitioners looking for guidance on scenario development, and on opportunities for further advances. It also updates modeling users (e.g., policy makers and their socio-technical advisors) on the latest methodological developments and issues, and their implications for the findings of scenario analysis.

1.2. Research methods

This research uses a qualitative synthesis approach ([Cassell et al., 2006](#)) to address the formulated research questions. Qualitative synthesis methods aim to bring together research findings about a topic of inquiry (in our case, scenario processes in socio-environmental systems analysis) from a range of meanings, perspectives, and experiences ([Barnett-Page and Thomas, 2009](#)).

Our synthesis activity has progressed through several steps. The first comprised pre-workshop activities, where the core research team (i.e. small group of co-authors) conceived the paper's idea. A preliminary literature review was then conducted to collect the main themes around which the paper was to be organized. This was presented at the outset of the workshop to set the context for the discussions. In the workshop preparation, we used purposeful sampling ([Suri, 2011](#)) to ensure access to key informants in the area who could bring rich and diverse experiences. Participants were invited with a view to maximize the group's expertise coverage and diversity (scientific, ethnic and gender). The workshop brought together experts, scholars and practitioners (approximately 30) working in the area of scenario development, covering a wide range of sectors related to socio-environmental systems analysis (i.e. water, energy, climate, agriculture, health etc.). Subsequently, notes from the workshop discussions were analysed by a smaller team of authors to identify dominant themes, which were further explored in the literature. These themes provided the basis for the research framework or the conceptual map around which the narrative of the synthesis was pulled together and reported. Through iterative cycles of writing and deliberation, a group of the workshop participants (the paper's co-authors) have contributed to the synthesis activity. Finally, the soundness of the qualitative synthesis produced by this research has been validated through the journal's independent peer review process involving several recognized experts ([Walsh and Downe, 2005](#)).

1.3. Research framework

There is no single approach in the literature for scenario development, there being a range of approaches and schools of thought ([Frame, 2018](#); [Slaughter, 2008a](#); [Slaughter, 2008b](#); [Sardar, 2010](#)). Yet, these approaches do share common characteristics: defining scope, identifying and analysing critical drivers for change and uncertainties, building scenarios, and evaluating scenarios. This article builds on the fundamental phases shared across these approaches, and identifies the challenges confronted during the implementation of scenario development. To serve this purpose, we have organized our research framework around two key dimensions (See [Fig. 1](#)):

1. The fundamental phases of scenario development: before, during, and after the creation of the scenarios. This generic view allows researchers and practitioners, operating under different methodological approaches, to link and contextualize the article's findings to their projects.
2. The key questions or information needs (e.g. managing uncertainty, understanding complexity) encountered through the process.

Sections 2–4 of this article explore what we consider to be the key questions for scenario development as listed in [Fig. 1](#), reflecting the key challenges noted above. We describe each issue in more detail and consider some examples of how they are addressed in various scenario exercises. We also point to the key remaining gaps and further work needed. [Section 5](#) follows up with suggestions for future research, which can cut across issue areas. Finally, we conclude in [Section 6](#).

2. Before creation (scoping and process design)

2.1. What is the purpose of the exercise?

Individual scenario exercises can serve multiple purposes or functions ([Pulver and VanDeveer, 2009](#); [Wiek et al., 2006](#)) including exploration, decision making, communication and learning. The exact purposes or goals of a scenario exercise should be clearly specified before embarking on the scenario development exercise and periodically revisited during the process. These goals will influence the nature of the process and the ultimate products, including the types of scenarios to be developed, the nature of stakeholders to be involved, and the methods to be used. In the course of a scenario exercise, each of the four purposes are likely to be functionally relevant, but at different stages, for different actors and to different degrees. For example, learning is oriented towards participants where scenarios can serve as boundary objects ([White et al., 2010](#)) to bring together different groups of stakeholders in a process that promotes knowledge co-production and social learning. Audiences such as the general public tend to focus more on the products than the process, assuming that issues of salience, relevance, and credibility have been properly addressed in the exercise ([Cash et al., 2003](#)).

With respect to the types of scenarios to be developed, [Maier et al. \(2016\)](#) has provided the following classification based on [Börjeson et al. \(2006\)](#). Predictive scenarios address the question “What will happen?”, exploratory scenarios “What could happen?”, and normative scenarios “How can a specific future be realised?”. These different types of scenarios require different methods. The former two usually reason forwards (projections, explorations) and are problem-focused, whereas the latter reasons backwards (backcasting) and are solution-focused.

2.2. Who should be involved in the development of the scenarios?

In scenario development processes, there is a core team that is responsible for designing and implementing the scenario process. Beyond the core team, participants representing various interest and stakeholder groups need to be actively engaged for reasons such as:

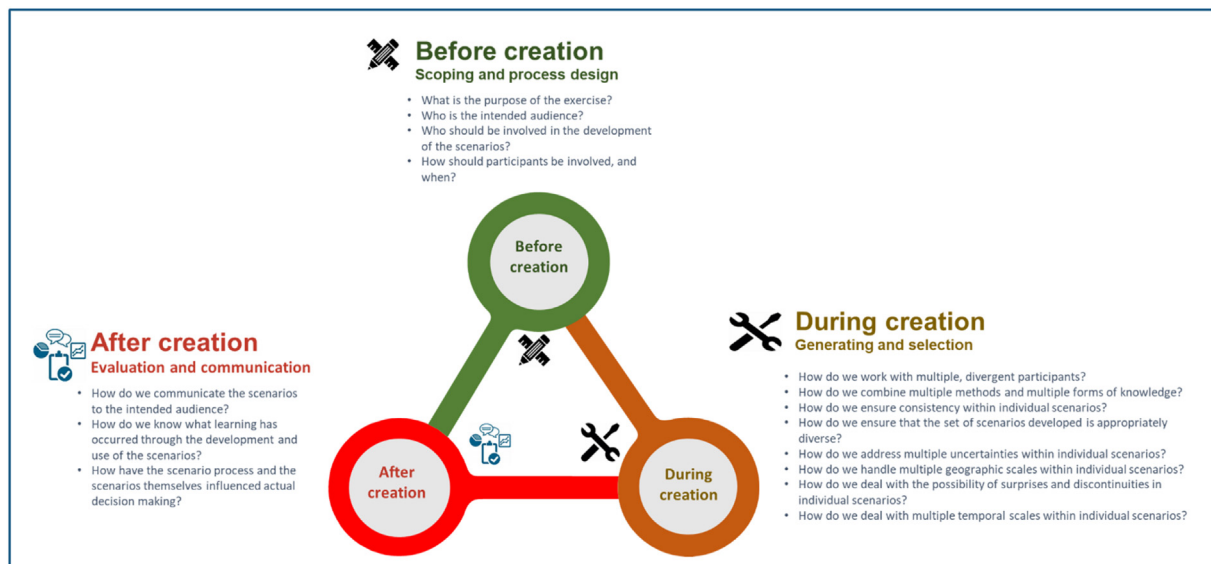


Fig. 1. The questions encountered during the scenario development process (before, during, and after scenario creation).

providing insights and knowledge; cultivating ownership of the process and its products; and ultimately promoting desirable changes (Quist and Vergragt, 2006). At the early stage of scoping, scenario process designers need to carefully consider who should be engaged, when and how, given the goals, scope and budget. This section discusses some of the issues related to these considerations.

2.2.1. Who should be involved?

The first issue relates to determining who is qualified to participate in that they are knowledgeable and seen as credible and legitimate representatives of a broad range of appropriate stakeholder groups (Morgan, 2014), possess the capacity to cope with uncertainties involved in the conceptualizing stage, and can open up the foresighting discussions.

Assessment of participants' potential contribution in a truly inclusive process can be challenging as it involves bringing together people with different cognitive styles, modes of understanding, and beliefs (Rounsevell and Metzger, 2010). Another challenge relates to reconciling the heterogeneity and minimal representativeness of invited participants to the broader interest and that of stakeholders. Andersen and Jæger (1999) propose the use of heterogeneous groups of actors, policy makers, business representatives, experts and citizens. This type of plenary involvement is commonplace throughout the scenario literature. Heterogeneous groups are seen as advantageous, as they provide diverging and new perspectives and knowledge, broaden the scope of the discussions and, in doing so, create interesting results (Ramirez et al., 2015). For example, Kok et al. (2006) invited poets and other free-thinkers to workshops for multiscale European and Mediterranean scenarios, while Van de Kerkhof and Wieczorek (2005) engaged individuals with unorthodox or innovative views to help identify long-term climate options for The Netherlands. Furthermore, depending on the purpose of the exercise, some groups, and the communities within them, should have a minimal representation in order to address within-group heterogeneity and power imbalances (Elsawah et al., 2015). When members of the general public are involved, the latest research suggests to guide them first through informational processes to minimize awareness gaps and misconceptions, and then involve them in scenario building as so-called informed citizen panels (Volken et al., 2018; Fleishman et al., 2010). However, the concept of informed citizen panels has also been critiqued as scientizing public discourse, potentially stifling the development of consensus-based, action-oriented solutions to environmental problems (Blue, 2018).

Various methods, ranging from formal and systematic to informal, can be used to maximize the diversity of participants. These methods include: the "CQI" method, or criteria for inclusion, minimum quotas and individuals (Gramberger et al., 2015); demographic data analysis (Chakraborty, 2011); and snowballing (Van de Kerkhof and Wieczorek, 2005). The total number of participants invited to any particular engagement varies from one study to another. For example, Chakraborty (2011) ran workshops with 100 and 300 participants; Kok et al. (2006) identified about 45 and invited 35; and Carlsson-Kanyama et al. (2008) held multiple workshops with between 12 and 20 participants. Another issue relates to the fact that some actors (e.g. future generations) cannot be engaged at all, raising the question about how they can be best represented in the process. Having said that, although future generations are not physically able to participate, scenario processes can build in an explicit consideration of their potential needs (e.g., Anderson et al., 2012).

2.2.2. How should participants be involved, and when?

Different scenario development stages call for different methods to involve participants, so most scenario processes will combine several methods (both qualitative and quantitative), compounding the challenge of choosing among methods. Several considerations should be taken into account in selecting methods, such as: how methods support the scenario functions at each stage as well as for the whole exercise (see Section 2.1); and how the outputs from each stage are intended to be used in subsequent stages. Another important consideration is how methods suit participants' individual characteristics (knowledge, experiences) and group characteristics (e.g. power relationships). For example, in a participatory exercise, qualitative techniques may be met with doubt regarding the subjective nature of the technique chosen, particularly if those involved are experienced in quantitative and/or analytical techniques (Drakes et al., 2016). Conversely, stakeholders may find quantitative techniques (e.g. modeling) intimidating and be left feeling ostracized from the process, leading to limited participation. When working with the general public, the scenario methods and materials should be adapted to their knowledge of the topic, numeracy, and computer skills (Volken et al., 2018; Xexakis and Trutnevyte, 2019).

There are various examples in the literature that illustrate how some of these difficulties of participatory processes can be alleviated. For instance, in order to engage participants' spatial orientation to their environment, Chakraborty (2011) provided them with physical pieces that can be moved around on a map. Aditya (2010) found that participants

preferred marking up transparencies to mobile GIS for conveying their understanding. [Elsawah et al. \(2015\)](#) used a variety of methods, gradually moving from the more qualitative to the more quantitative in the course of their study. Participants' mental models were made explicit through cognitive mapping, and provided the conceptual basis for the development of an agent-based model. In a study on forest-using communities, [Wollenberg et al. \(2000\)](#) found that power differences both within and between communities and officials were too severe for learning to take place during a joint workshop. They used separate scenario workshops to engage relatively cooperative stakeholders, while using the outputs to communicate interests between antagonistic groups. [Macmillan et al. \(2016\)](#) used a silent negotiations procedure in order to give various stakeholders an equal say without anyone having the ability to override the inputs of the others. Other existing methods of stakeholder and public engagement, such as expert consensus conferences, value-tree analysis, or public hearings, can also be adapted to scenario applications ([Renn, 2015](#)).

Whereas sufficient time investment is needed to include and process the diverse contribution from participants ([Gramberger et al., 2015](#)), it can be challenging to plan ahead to ensure that stakeholders will make this time investment through sustained engagement. Some stakeholders can find it difficult to attend multiple events or respond to multiple interviews, whether because of "stakeholder fatigue" ([Carlsson-Kanyama et al., 2008](#)), or because participants are constrained by their own responsibilities. Some of these risks can be mitigated through careful process design that clearly considers the required contribution from participants at every stage of the scenario process. Each stage (e.g. scoping, creation) will likely require different kinds of inputs from different groups. Although it is not essential to engage all groups at all events, it is still crucial to incorporate their evolving insights into the process and maintain a sense of continuity and identification with the product. For example, [Kok et al. \(2006\)](#) sought to involve stakeholders throughout the scenario development process, taking steps to maintain participation across workshops. Yet, they did not include the freethinkers in every activity, because their role was to stimulate broad thinking for the scenario storylines.

3. Creation (generation, selection)

3.1. How do we work with multiple, divergent participants?

As mentioned in [Section 2](#) it is a well-accepted premise that working with multiple groups and stakeholders brings several benefits to scenario development. However, the implementation of an effective stakeholder engagement process for scenario creation can be challenging, especially when engaging groups with diverse perspectives, competing interests and various levels of agency and power ([Cairns et al., 2013](#)). Here, we discuss some of these major challenges and how they are addressed in the literature.

3.1.1. Collecting and combining multiple views

Different stakeholders will have different goals, preferences and values that stem from their various lived experiences and backgrounds, and positions in the system. The core scenario team has to collect, compile and integrate the generated information in a meaningful way to produce scenarios that serve the exercise purpose. There is an analytical challenge of collating and resolving conflicting information and creative tensions to generate useful information, as well as the challenge of ensuring that the process of creating scenarios is fair and inclusive towards participants.

One risk during scenario generation is that the spoken views of workshop participants may be dominated by individuals or subgroups, such as those in certain power positions, with certain personality traits, or of a particular gender, age or ethnicity. In such situations, it may be appropriate to group participants to ensure that a wider set of views are provided (e.g. [Tschakert et al., 2014](#)). However, this can be

expensive and demanding for both participants and the core team ([Lebel et al., 2005](#)). A crucial factor is the role and competence of the scenario workshop facilitators, and whether they can appropriately manage the inevitable risks of the discussion being dominated by more outspoken individuals, and allow all participants the opportunity to express their views and partake in fair deliberation focused towards the objective of the exercise. The facilitator's experience and domain knowledge are fundamental in establishing contextual boundaries, and converging and integrating numerous ideas. Facilitators must be cognizant of the nature of the methodology employed (quantitative vs. qualitative) and its suitability to the experience and learning capacity of the stakeholders engaged. Overlooking this dimension may cause cognitive dissonance and lack of ownership from participants, jeopardizing the process and potential effectiveness and impact of the scenarios.

Various methods for consensus building and group decision making can be used to help neutralize and consolidate views in order to generate useful information and scenarios. These methods include: the Delphi technique ([Nowack et al., 2011](#)), multi-criteria analysis ([Cavallaro, 2009](#)), Cross Impact Balance analysis ([Weimer-Jehle, 2006](#)), silent negotiations ([Macmillan et al., 2016](#)), and multiple other methods that are used for stakeholder and public engagement ([Renn, 2015](#)). In all these cases, it is important to ensure that every participant's view is elicited and documented before proceeding to any consensual group judgement ([Morgan, 2014](#)). In this way, a balanced picture of everyone's views can be achieved.

3.1.2. Managing expectations about the scenario process and products

Managing the expectations of participants is another challenge. Failing to do this well may lead to disappointments later and jeopardize the perception of the effectiveness and impact of the process and its products. Through engagement itself, participants may develop potentially unrealistic expectations (e.g. about the utility of expected output or stakeholder ability to influence and use results). Working with participants who represent diverse interests places additional responsibility on the scenario team to crystalize the purpose of both the process and the results. More often than not, the intended outputs from the process are conveyed to participants, but the purpose and rationale of the process and the implicit pedagogical benefits are under-emphasized or mismanaged, leading to participants having unrealistic expectations of the process ([van Asselt Marjolein and Rijkens-Klomp, 2002](#)). Along similar lines, there may be experts or stakeholders who have somewhat ulterior motives for participation. This includes "entrapment" by experts in the scenario team who use participants superficially to validate their existing research results, or "co-option" of experts by stakeholders seeking personal or institutional advantage ([van Asselt Marjolein and Rijkens-Klomp, 2002](#)). Effective communication and transparency of the process (see [Section 3.1.3](#)) is key to managing expectations on both sides.

These challenges highlight the complex nature of scenario development, the importance of improving the objectivity of participatory methods, the need for greater emphasis on the evaluation of participant involvement in the scenario process, and the overall ethical conduct of scenario teams ([Becu et al., 2008](#); [Gramberger et al., 2015](#)).

3.1.3. Process communication and transparency

In general, scenario communication emphasizes the results of the process ([Section 4.1](#)), rather than the process itself. Scenarios are typically developed by a group of stakeholders, experts, and/or modelers, which raises the general issue of how legitimate the resulting scenarios are ([Xexakis et al., under review](#)). It is therefore of utmost importance that the process is well-designed but also clearly and transparently communicated. A related issue is the reproducibility and scientific quality of the process, and how this information is communicated ([Carlsen et al., 2017](#)). All too often, information in the literature on the details of the process is scarce. Important issues include transparency of criteria

for stakeholder engagement and, where possible, providing a complete list of the participants who were involved. One useful method already mentioned is the CQI method described by Gramberger et al. (2015). As noted in Section 2.2, this method can be used to select stakeholders with the desired criteria (e.g. expertise) to participate in the process. The use of a structured method can help to communicate who was present, why they were present, and who was not. Another related issue is the transparency of who created what. Alcamo (2008), for example, distinguished between a Panel (external stakeholders), a Team (project members), and Modeling groups that all have specific roles, with the external stakeholders being responsible for developing narratives, while modelers determine the translation from stories to model input.

3.2. How do we combine multiple methods and multiple forms of knowledge?

One of the challenges is the fundamental hybridity of scenario exercises that need to combine multiple – quantitative and qualitative – forms of knowledge, methods and data types during scenario development (Kosow, 2015; Trutnevyte et al., 2014; Trutnevyte et al., 2016). This hybridity largely constitutes their appeal, but also raises considerable challenges, as these scenario approaches need to bridge epistemological and methodological gaps (Kosow, 2016; Geels et al., 2016).

In regard to *knowledge*, the challenge consists of balancing scientific knowledge, stakeholder and local perspectives, and creativity. To provide relevant orientation and futures knowledge, scenarios must be anchored in accepted problem definitions and knowledge pools. At the same time, they have to deal with the knowledge gaps we have with regard to what might come. In addition, there are also the unknowables, which have consequences for scientific modeling (Beven and Freer, 2001). First, tensions can arise between things we (believe we) can know on the one hand and the future's openness and uncertainty on the other hand. Second, tensions can also arise between different sources of knowledge, including knowledge based on scientific evidence, on other more anecdotal or local forms of evidence, such as stakeholder perceptions, native and traditional knowledge, or on the specific visionary and overview knowledge of futurists. Currently, it is mainly up to the experience and preferences of the scenario building team if and how uncertainties and unknowns as well as different sources of knowledge are dealt with. Scheele et al. (2018) provide guidance on how the scenario method of Cross Impact Balances could be used to inspect and synthesize different sources of knowledge and uncertainties.

In regard to methods, quantitative methods often are based on a rather positivist stance, aimed at quantitatively and objectively calculating the future. Qualitative methods on the other hand are rather marked by a constructivist perspective, aiming at qualitatively visioning and idiosyncratic images of the future (Grunwald, 2014). Clearly, current combined scenario approaches mix these methods in many diverse ways and often cannot be simply attributed to a purely constructivist or positivist paradigm. For instance, there are approaches where quantitative models are explicitly used as input into constructivist exercises, as for example in participatory modeling (Van den Belt, 2004). Still, the hybridity and heterogeneity within combined methodologies can introduce (sometimes latent) tensions and challenges into their complex processes. Conflicts regarding standing, impact and credibility of the modelers on the one hand, and the stakeholder groups responsible for the qualitative scenarios (or storylines) on the other hand, have been described in a paper by Volkery et al. (2008) entitled: "Your vision or my model". The decision whether, for instance, the model or the storyline is the final benchmark can have an effect on the character and content of the resulting scenarios.

The final issue relates to combining, merging and translating data from quantitative and qualitative exercises. This may involve assigning numbers to qualitative inputs (Van Delden and Hagen-Zanker, 2009), aligning quantitative model structure with

boundaries set in a qualitative exercise (Lempert et al., 2003), as well as using the quantitative model outputs to revisit the qualitative side of scenarios (Trutnevyte et al., 2014). Several techniques have been proposed to merge and translate data from quantitative and qualitative exercises, ranging from intuitive approaches (e.g. ad hoc expert judgments) to more formal approaches, such as fuzzy logic (Alcamo, 2008), cognitive maps (Elsworth et al., 2015), fuzzy cognitive maps (Van Vliet et al., 2010), Bayesian statistical reasoning (Kemp-Benedict, 2010), expert elicitations (Morgan, 2014), and roadmaps to develop spatiotemporally-explicit biophysical inputs (Booth et al., 2016). Mallampalli et al. (2016) give a comprehensive overview on the current state of art and provide a decision matrix to support scenario developers in their choice of translation method.

3.3. How do we ensure consistency within individual scenarios?

Consistency is a principle of scenario creation (and selection) – and is understood as a safeguard against what can be perceived as arbitrariness of scenarios (Kosow, 2015). Whilst the term "consistency" is commonly used by various scenario communities, mostly it is weakly defined with little consensus (Tourki et al., 2013). Consistency refers to two issues: scenarios' internal consistency and agreement between scenario parts that are analysed qualitatively versus quantitatively.

Ensuring the internal consistency (i.e. freedom from internal contradictions) of the scenario is primarily a concern for qualitative scenarios (also called storylines, or narratives). Qualitative scenarios consist of assumptions on how the different pieces of the scenario, the scenario factors (also called drivers, variables or descriptors), will play out in the future. These assumptions are subject to human cognition biases and social effects at play in the group of stakeholders and experts developing the storylines (Morgan and Keith, 2008). If these assumptions on interrelations between future developments are not carefully considered, internal contradictions for the scenario overall might appear. This is one of the major reasons why storylines are frequently criticized as being 'unscientific' (e.g. Rounsevell and Metzger, 2010). One prominent example is the internal inconsistencies unravelled by Schweizer and Kriegler (2012) in their attempt to reconstruct scenarios from the *Special Report on Emission Scenarios* (SRES) published by the Intergovernmental Panel on Climate Change, or IPCC (Nakicenovic et al., 2000). Schweizer and Kriegler (2012) used Cross Impact Balances (CIB) to analyse the qualitative scenarios (the storylines) and SRES model results with regard to their assumptions on interrelations between scenario factors. They examined the degree to which the SRES sample would have looked different if CIB had been used for scenario development—instead of the intuitive logics that were in fact used for this exercise. They discovered the following issues. First, taking the logic of the assumed interrelations between future developments as a criterion for internal consistency, model realizations of the SRES storylines vary widely in their ability to remain consistent with the qualitative storylines on which they were based (Schweizer and Elmar, 2012). Second, a number of "coal-powered growth" scenarios (again based on the SRES assumptions on interrelations) that are fully internally consistent were absent from the SRES sample. These issues with the internal consistency of storylines can hinder their credibility and thus their usefulness and potential impact.

A multitude of methods have been developed to measure and manage the internal logical consistency of qualitative scenarios, known under headings like morphological analysis (Zwicky, 1969; Ritchey, 2018), consistency analysis (e.g. Rhyne, 1971), Formative Scenario Analysis (FSA) (Scholz and Tietje, 2002), and CIB (Weimer-Jehle, 2006). Different methods use different approaches to measure and assure scenario consistency; for overviews see Tourki et al. (2013), Kosow (2016), and Carlsen et al. (2016a). In the field of technological forecasting, these formal, (semi-) quantitative and computer-aided, consistency methods, are standard approaches to construct qualitative scenarios and/or to test their consistency. The environmental research community has only very recently started to consider using these

systematic techniques instead of methods based on Intuitive Logics (Rounsevell and Metzger, 2010; Carlsen et al., 2017). Current approaches can be applied, but have their limitations. For instance, experience has shown that CIB can perform comprehensive consistency tests for a moderate number of scenario factors (i.e. 12–20 factors, each with up to ca. 4 states). For scenarios with a greater number of factors or dynamics that cross scales, CIB still identifies scenarios depicting the strongest tendencies of the system through a Monte Carlo approach. However, such scenarios may not be the most informative for a risk analysis (cf. low probability but high impact scenarios, so-called “perfect storms”). There have been some methodological advancements for CIB to handle cross-scale dynamics (Hansen et al., 2014; Schweizer and Kurniawan, 2016; Kemp-Benedict et al., 2019), but work is ongoing.

The second issue of consistency relates to assuring agreement or compatibility between qualitative and quantitative parts of the combined or integrated scenarios. This is linked to the discussion in Section 3.2, and is particularly relevant to the use of the SAS approach in environmental change research (Alcamo, 2008). In SAS, a qualitative scenario provides guidance for a numerical model simulation. The basic idea is that modeling and simulation can be used to identify any inconsistencies in the qualitative scenario. However, this “consistency check” by numerical models has two major limitations. First, it is limited to the quantifiable parts of the qualitative scenarios (Kemp-Benedict, 2012). Second, it is difficult to realize in practice (Volkery et al., 2008) due to the large degrees of freedom in both the creation of qualitative scenarios and running of complex models. Moreover, several different quantitative scenarios can be consistent with one storyline (Trutnevyte et al., 2011, 2012), and several storylines can be consistent with one and the same quantitative model output (Beck, 2018). In sum, open questions remain on if and how to compare, and potentially mutually adapt, the assumptions and logic underlying storylines and numerical models (Kosow, 2015, 2016; Beck, 2018).

3.4. How do we ensure that the set of scenarios developed is appropriately diverse?

Given the challenges in connection with interacting human and environmental systems, including possible irreversibility and tipping points (e.g. Lenton and Ciscar, 2013), it is important to strive for broad coverage of future possibilities when constructing scenario sets and selecting scenarios; that is, to exploit scenario diversity. For example, in an ex-post analysis of the SRES storylines (Nakicenovic et al., 2000) using Scenario Diversity Analysis (SDA), it was shown that the storylines of the SRES emission scenarios were not maximally diverse (Carlsen et al., 2016a). Put simply, ensuring diversity means that the scenarios in a set should be as different from each other as possible.

When developing options for strategies, an often-used argument is that they should work reasonably well for a wide range of external conditions, and in a scenario process those conditions can be framed as a set of scenarios (Van Vliet et al., 2010). For example, the scenario-axes approach (van't Klooster and van Asselt, 2006), which is based on a basic matrix (e.g. 2×2 dimensions), allows for an exploration of the selected drivers. However, it overlooks the role of other multidimensional uncertainties (Trutnevyte et al., 2016), and does not necessarily offer the largest diversity relevant to the problem definition, an issue that can be solved by framing scenarios on solution-focused axes (Maier et al., 2016). Hence, if the selected set of scenarios is too narrow, one runs the risk of the test of the strategies' robustness being too restrictive.

A suitable point of departure for analysing and comparing current efforts in addressing scenario diversity is morphological analysis (Zwicky, 1969; Ritchey, 2018). In such analysis, scenarios are expressed by means of (scenario) factors (alternatively drivers, variables, determinants) where each factor is a discrete variable that can take a finite number of mutually exclusive states (alternatively variants). A specific problem with diversity analysis is the potential issue of ‘combinatorial explosion’ of the possible number of sets of scenarios for a given number

of scenarios ($n!/(k!(n-k)!)$), with n the number of scenarios and k the number of scenarios in a set), which makes this a computationally demanding task for problems involving larger numbers of factors, states and scenarios. In several approaches, inconsistent state combinations (see Section 3.3) are identified as making the topology of the morphological space even more complicated to navigate.

Earlier attempts to address scenario diversity assume that the factors of the morphological space be nominal. Hence, the distance between two scenarios is defined as the sum of the drivers for which the states are different (Tietje, 2005). One problem with this approach is that with all variables specified as nominal, the optima often become indistinct because large numbers of scenario sets will be lumped together in fewer groups by the distance metric. A few approaches have been developed recently for addressing this shortcoming. The latest methodologies for scenario diversity are summarized by Berntsen and Trutnevyte (2017) and include: SDA (Carlsen et al., 2016a, 2016b); OLDFAR, or the Optimized Linear Diversity Field Anomaly Relaxation method (Lord et al., 2016); Distance-To-Selected Method (Berntsen and Trutnevyte, 2017); Modeling to Generate Alternatives (Berntsen and Trutnevyte, 2017); SPREAD (Hennen et al., 2017); and adapted scenario discovery cluster analysis (Guivarch et al., 2016), or principal component analysis (Densing et al., 2016), among others.

Fig. 2 illustrates scenario set diversity and also relates this to (internal) scenario consistency; see previous sub-section. For this simple example with only three factors in the morphological field (Fig. 2a), the scenarios and a maximally diverse set can be illustrated in a three-dimensional cube (Fig. 2c). Note that in general, there is no simple relationship between scenarios being part of a set of maximally diverse scenarios and consistency. The scenarios in a maximally diverse set can be inconsistent as well as consistent. In a real case, both approaches need to be applied in tandem.

3.5. How do we address multiple uncertainties within individual scenarios?

The complexity of any socio-environmental system under study leads to numerous uncertainties and a great deal of incomplete knowledge that must be taken into account. Uncertainties in SES stem from: (i) competing theories or models to represent the forces that shape the future of the system (i.e. structural uncertainty), (ii) lack of informative data and poor data quality to precisely characterize the system (i.e. parametric uncertainty), (iii) fundamental uncertainty about future evolutions of part of the system, especially involving long-term scenarios, surprises or “unknown unknowns”, and/or (iv) different worldviews and preferences in the evaluation of future developments. Characterizing uncertainty requires understanding and defining what uncertainties apply to the study at stake, to identify which drivers and processes matter for the system evolution and its outputs of interest, how they impact on future evolutions, and how uncertain these drivers are. This definition is a challenge because analysts – and/or participants in the case of participatory scenario approaches – may not know or agree on the uncertainties that matter most. Surprises or unknown unknowns are particularly difficult to deal with (see Section 3.7).

To identify uncertainties that matter in SES, techniques such as global sensitivity analyses (Saltelli et al., 2008) allow systematic exploration of the model parameter space to calculate the effect of individual parameters on the model's results. Methods such as that of Sobol decompose their direct effect and their interaction effects with other parameters and provide associated sensitivity metrics/indices (Sobol, 2001; Campolongo et al., 2007). Thus the results of sensitivity analyses help identify those parameters with the most crucial influence on the model's results, which can inform how to simplify the problem of dealing with multiple uncertainties and which are the main ones on which to focus the analysis (Saltelli, 2002). The approach to identify critical uncertainties that matter using global sensitivity analysis has the advantage of being systematic and effectively screening all parameters,

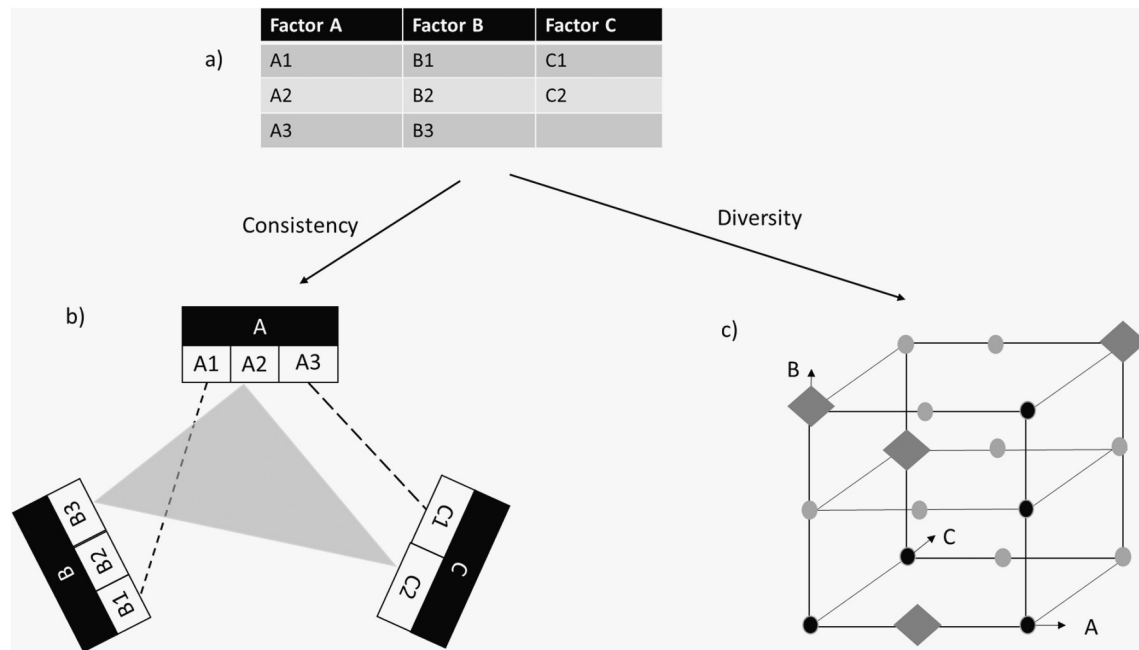


Fig. 2. Simple illustration of internal scenario consistency and scenario set diversity. Fig. 2a shows the morphological field built up from three factors A, B and C, with three, three and two possible states respectively. In this example two state combinations have been deemed infeasible: A1 and B1 as well as A3 and C1. In Fig. 2b this is indicated by dashed lines. All scenarios containing these two combinations are infeasible (seen as black dots in Fig. 2c), hence 13 scenarios are feasible for internal consistency and diversity analysis (seen as grey markers in Fig. 2c). A internally consistent scenario is illustrated by the grey triangle in Fig. 2b, and a maximally diverse scenario set is illustrated by the set of four diamonds in Fig. 2c.

thereby facilitating the covering of counter-intuitive cases. However, it is constrained by the structure of the models used, and thus cannot account for structural uncertainty. It is also unable to deal with surprises, and different outcomes arising from different assumptions and modeling boundaries. Formal sensitivity analysis can also be compromised if the model run-time is so long as to not allow sufficient sampling of the parameter space to obtain converged values of sensitivity metrics.

Participatory approaches can be better suited to address these cases, using the knowledge and creativity of participants to explore broader uncertainties than what are represented in models (Elsawah et al., 2020). For example, Barnhart et al. (2018) present a co-production and uncertainty-centred approach for watershed modeling, where experts and stakeholders work together through iterative cycles of characterizing, calculating, and conveying (3C's) uncertainties. In addition to global sensitivity analyses, further methods are being increasingly developed and used for working with large ensembles of modelled scenarios (Guivarch et al., 2017; Trutnevyte et al., 2016). Fu et al. (2020), for example, undertake a deterministic, as opposed to a probabilistic approach where one samples parameter space adaptively, starting with worst and best cases in terms of assumptions, and learns throughout the process. Their process of analysis potentially reduces sampling by casting it as a process of finding patterns and formulating questions within the ensemble of scenarios that merit further examination, allowing end-users to make the decision as to what underlying assumptions should be accepted, and whether uncertainties have been sufficiently explored.

3.6. How do we deal with multiple geographic scales within individual scenarios?

Stakeholders at different geographical and sectoral scales have different perspectives. Policy sector winners and losers may differ by scale, and different sets of issues and opportunities come into focus at different scales. Multi-scale scenarios can take these issues into account and can thus add particular value when assessing interactions across scales and possible trade-offs (Patel et al., 2007). Multi-scale scenarios

are common, with a number of good conceptual and practical papers (Zurek and Henrichs, 2007; Biggs et al., 2007). The Millennium Ecosystem Assessment (MEA) has been instrumental in advancing multi-scale scenario development methods, with its close to 40 so-called sub-global assessments (SGAs) in addition to the global scenarios (see Lebel et al., 2005). Key to the method of the MEA was a downscaling of the global narratives, after which they could be used to create quantitative scenarios and model input/output. To date, this method of downscaling qualitative scenarios, that in turn can be used as starting points for more local scenario development, is the most common way to deal with multiple scales. In the same vein, most global scenario sets for climate change research, including the IPCC SRES scenarios and the Shared Socio-economics Pathways (O'Neill et al., 2014), have been geographically downscaled to continental, national, and even sub-national scales (see e.g. Absar and Preston, 2015; Frame et al., 2018). Direct downscaling of quantitative trends or model outputs is a second method that is often applied (e.g. Verburg et al., 2008).

However, the strong legacy of the multi-scale scenario development work within the MEA seemed to have held back progress in using more novel methods. Yet, this has recently changed, and current efforts to develop multi-scale scenarios are taking new directions (Guivarch et al., 2017; Mason-D'Croz et al., 2016). An example is the effort to explore scenario construction beyond the "two-axes approach" (i.e. two main driving forces are identified intuitively and plotted along two axes, thus defining four scenario quadrants in which storylines are developed), to new methods such as CIB (Schweizer and Kurniawan, 2016; see Sections 3.3 and 3.4) or Field Anomaly Relaxation (Lord et al., 2016). These methods allow for a more structured cross-scale comparison and analysis. Another field of recent progress relates to the recently developed global scenarios for climate change research – Shared Socio-economic Pathways (SSPs) and Representative Concentration Pathways (RCPs). O'Neill et al. (2017) invite other research groups to use, explore, and extend the SSPs to other sectors and geographic scales. Indeed, since their release, the SSPs have been used in multiple studies, globally but also sub-globally, for example by Absar and Preston (2015) who use the Factors, Actors, Sectors approach to ensure cross-scale consistency in downscaling the SSPs for the United States. In Kok et al. (2019), the

global SSPs are downscaled for Europe, combining them with a set of existing European scenarios and this has also been developed in New Zealand (Cradock-Henry et al., 2018; Frame et al., 2018; Ausseil et al., 2019) and in the Barents Sea (Nilsson et al., 2017). Rault et al. (2019) suggested a participatory approach to blend local vision and knowledge into writing narratives flowing from the global scenario models, and using these narratives to drive quantitative evaluations.

3.7. How do we deal with the possibility of surprises and discontinuities in individual scenarios?

Socio-environmental system problems are rife with uncertainties, and one extreme form of uncertainty is that of surprises (Toth, 2008). Surprises (including wildcards and black swans) often result in discontinuities – “a temporary or permanent, and sometimes unexpected, break in a dominant condition in society” (van Notten et al., 2005). Surprises in SES occur as a result of the large and complex interactions in the coupled socioeconomic and environmental systems, and according to Dawes (1988) the mismatches between subjective and frequentist probability judgments. Our focus here, however, is less about the nature of surprises and discontinuities and more on the relationship of surprises and discontinuities to scenario systems analysis. We direct the reader to existing typologies for surprises and discontinuities (e.g., Kates and William, 1996; Myers, 1995; van Notten et al., 2005; Toth, 2008; van Rij, 2013), primarily related to our ability to have foreknowledge about their occurrence. Toth (2008) also distinguishes between isolate, interactive, and propagating surprises, depending on how they affect various systems. Many authors point to the potential value and importance of scenarios for identifying and exploring the effect of surprises and discontinuities (e.g., van Notten et al., 2005; Toth, 2008; Saritas and Smith, 2011; Read, 2014). At the same time, many of these same authors point out that there is a dearth of scenario exercises that have explicitly explored surprises and discontinuities (van Notten et al., 2005; Read, 2014). This reflects, in part, the difficulties in trying to explore surprises and discontinuities in scenarios.

Firstly, almost any scenario exercise requires a certain amount of suspending disbelief (Frittaion et al., 2010) but more so if incorporating surprises and discontinuities. Defending any specific surprise or discontinuity can be difficult. Secondly, the methods used to develop scenarios can limit our ability to include surprises and discontinuities. Read (2014, p. 61) argues that the commonly used two-axes approach (see Section 3.4) “tend to trap participants in focusing only on the interplay” of these drivers. In addition, quantitative models simulating long-term developments are often not designed to reflect the effects of significant acute shocks and “blow up” when these are introduced. Maier et al. (2016) note that, in dealing with surprises, models may need to be altered to include new processes, which can be a challenging task for the modelers. Third, there can be concern that whatever surprise is introduced will introduce impacts that obscure the effects of longer-term trends, or particular decisions. This can detract from the main insights that may be desired from the scenario exercise. However, for surprises that are the result of critical tensions arising from intersecting trends (van Rij, 2013), this need not be the case. At the same time, these types of surprises can be scenario dependent, and therefore would not lend themselves to being explored in all scenarios in a scenario set, which may be a goal in a particular exercise.

Despite the issues raised above, and others we may not have discussed, efforts have been made to improve foresighting around surprises in three ways. Firstly, many studies have focused on identifying potential surprises or wild cards but have stopped short of introducing them into scenarios. Petersen (1997) represents an early example of identifying a large number of possible surprises. More recent efforts include: the iKNOW project (<http://wiwe.iknowfutures.eu>); the Big Picture Survey (Saritas and Smith, 2011); and an analysis of wild cards in transport (Hauptman et al., 2015).

As a second way to improve foresighting, some studies introduce surprises as a means of stress-testing already developed scenarios. For example, Smith and Dubois (2010), describe how wild cards were applied, ex post, to three spatial scenarios for the future of land use in Europe. The use of wild cards offers a systematic approach for conceptualizing a surprise along the dimensions of Mendonça et al. (2004): process (e.g. sudden change vs creeping change), plausibility (e.g. imaginable but improbable), topic (e.g. economic), break type (e.g. dead end), time (e.g. immediate vs delayed), and impact (e.g. local vs multi-level). Separate “red teams” could be also created and mandated with a task to challenge model-based scenarios for potentially relevant surprises and discontinuities (Trutnevyte et al., 2016).

Thirdly, surprises can be integrated more directly into the development of scenarios either by prompting study participants to respond to them or by augmenting scenario thinking with computational techniques. Read (2014) presents the use of Foresight Scenario Planning (see Briggs, 2010; Briggs and Briggs, 2011) as a means for introducing surprises in scenario development processes. For computational approaches, Schweizer (2020) found that developing scenarios with the help of an algorithm, specifically the CIB, could reveal internally consistent surprises (see Section 3.3) for socio-economic scenarios arising from intersecting trends. Another approach uses what are referred to as ‘serious games’ (Lawrence and Haasnoot, 2017), which have been used for several purposes, such as communicating uncertainty (Van Pelt et al., 2015) and promoting social learning (e.g. van der Wal and Merel, 2015).

3.8. How do we deal with multiple temporal scales within individual scenarios?

Several issues come to the surface when dealing with the temporal scale of scenarios. What is the time horizon for the scenario, that is, how far into the future does it look? Does the scenario describe the path leading from the present to the future or provide only a picture of the future at the end of the time horizon? Assuming the former, how many of the intermediate states are described, that is what is the temporal resolution of the scenario?

The first of these questions arises because: 1) different stakeholders can have very different time horizons; and 2) different processes play out at very different time scales. Politicians or other social planners often have a medium- to long-term time horizon (e.g. 20 years), while local stakeholders at the household or community level often have a much shorter time horizon (e.g. 1–5 years). Scientific researchers may have even longer time horizons, e.g. > 100 years (e.g. Nakicenovic et al., 2000) with some extending this to 1000 years such as in Cocks (2003). The much longer-term horizons are often related to the time scale of natural processes, for example that of climate change, but this can also apply to social and economic changes that can take many years, for example a major change in energy infrastructure. With respect to the second question regarding the time scale of processes, two types of scenarios can be distinguished: endpoint and pathway scenarios (Van Notten et al., 2003). Endpoint scenarios describe the state of a system at some time in the future; how this endpoint is reached is only implicitly addressed. Pathway scenarios describe a path or development towards a particular end-state and are also referred to as developmental, chain, transient or time-dependent scenarios (e.g. IPCC, 2000; Van Vuuren et al., 2011). Both types of temporal scales are also used in combination. For example, a normative endpoint scenario is used in transition or backcasting studies on pathways to arrive at a desired future (e.g. van der Voorn et al., 2012).

Describing a pathway can help to justify a possible endpoint or to account for the following: discontinuities (see Section 3.6; Guivarch et al., 2016), the timing of events that are relevant for decision making over time, and the path-dependency of decisions (Haasnoot et al., 2013). A pathway can also explore dynamics between (external) scenarios and responses of actors (Eisenhauer, 2016). Pathways can also be used to

communicate about possibilities, choices and trade-offs and bring together multiple perspectives and approaches in a dialogue (Rosenbloom, 2017). For example, pathway scenarios have been used in a game setting to raise awareness about uncertainty in climate change and natural variability (Van Pelt et al., 2015) and about decision making under uncertainty (Lawrence and Haasnoot, 2017). Lempert (2013) argues that considering multiple time scales can be useful in communicating the scenarios.

4. After creation (communication, evaluation)

4.1. How do we communicate about scenario results?

4.1.1. Selecting and formulating scenario indicators

Many ways can be used for communicating scenario results, the selection and complexity of which have significant implications for how results are interpreted. However, only recently has discussion in the scenario literature started in terms of awareness of the multiple dimensions of indicators and challenges, and in how the right types and formulations of indicators should be selected for different purposes (Trutnevyte et al., 2016). The multiple dimensions of indicators include purposes, types and formulations. Different scenario indicators may be selected for different purposes, which are closely related to the purpose of scenario development and its use in general. Lyytimäki et al. (2013) summarized three forms of indicator usage: 1) instrumental usage directly relating to decisions (e.g. concentration of a toxic contaminant in water can be used to compare with a water quality guideline for direct actions); 2) usage for long-term strategic development and planning (e.g. improvement in ocean fish stock can be used as an indicator for planning to aid further discussion and decision making in marine conservation, not as “absolute truth” providing immediate answers); and 3) conceptual usage for enlightenment and learning (e.g. an ecological footprint is used as a general concept to frame environmental sustainability). In addition to indicator types, there is also a question about how the selected indicators should be formulated. Examples of formulation include measures of performance that are related to reference point(s) (e.g. increase in fish population), or measures of efficiency that report value per unit (e.g. fish population per unit area). Biases can be introduced by using a particular formulation of indicators without clarity in the context, which may hinder the appropriate use of scenarios (Fu et al., 2017).

4.1.2. Visualizing scenario output

Visualizing scenario output is not just for aesthetic purposes, but effective visualization tools can facilitate better understanding of the scenarios, and what they convey about the future (Spiegelhalter et al., 2011). Some stakeholders may only be able to form an opinion about a scenario output if they can visualize options, especially when it involves trade-offs among several objectives. Effective visualization can help distil the key information without being overwhelmed with the modeling details. The effectiveness of a visualization technique depends on the problem at hand, considering factors such as the audience, the intent of the message to be communicated (e.g. communicating about trade-offs, scenario pathways), as well as the data types (e.g. spatial data, narratives). As in any example of science communication, it is also not always possible to anticipate how the scenario visualizations will be perceived by the intended audience without their actual testing (Xexakis and Trutnevyte, 2019; Trutnevyte et al., 2016).

In scenario discovery and associated studies, a key challenge is communicating about large scenario datasets to allow for understanding impacts, especially from a multi-objective and trade-off viewpoint. Due to the curse of dimensionality, traditional visualizations (e.g. the scatter plot) are inadequate tools in visualization of a high dimensional objective space. Some developments to tackle this challenge include efforts around:

- Data reduction (compression) methods, where the size of the dataset can be reduced by not including every data point. Methods include (Liu et al., 2014): filtering (bounding the data so that not all is displayed) and sampling (displaying the full bounds but drawing subsets within those bounds).
- Online Analytical Processing (OLAP), which is commonly applied in data mining and other exploratory analysis applications with large data sets. It allows a decision maker to apply intuition by slicing, dicing, drilling down, rolling up or computing pivots of the hyper-dimensional data space representing scenario sets (Curry and Ross, 2015).
- Human interaction methods, which use multiple coordinated views and animated transition (Scherr, 2009).
- Interactive tools with access to large scenario databases that allow the intended users to select scenarios of interest (Xexakis and Trutnevyte, 2019); for example the Scenario Explorer, an ensemble of over 400 peer-reviewed emissions pathways (Huppmann et al., 2019).

In scenario studies that integrate a large number of disciplines and processes, it can be difficult to provide a comprehensive overview of what is in the scenario. Listing impacts on a large number of indicators is often not easy to interpret but visualization techniques such as spider diagrams can help in providing such an overview. In addition, artist impressions, animations and rich pictures can be beneficial in portraying the key message of a scenario.

Another challenge relates to understanding and mitigating the possible biases in the audience's interpretations, which may ultimately lead to over or less confidence in the results (McInerney et al., 2014; Sacha et al., 2015). For example, rescaling results through visualization can invite systematic biases. McMahon et al. (2015) found that a group of novice readers, who were shown a graph of climate change projections, misinterpreted the intended message about the role of socio-economic factors in the IPCC scenarios. In the case of long-term energy scenarios, two related studies showed that an interactive tool with access to a large scenario database is not advantageous in terms of user engagement, and that it could overcomplicate communication as compared to a regular SAS approach (Xexakis and Trutnevyte, 2019) or even 30 pages of written text (Volken et al., 2018).

4.2. What learning has occurred through the development and use of the scenarios?

Inducing learning about the interplay of human and natural systems is one of the key aims of scenario analysis. The whole field of policy-oriented environmental and sustainability sciences, however, has been argued to have an underdeveloped theoretical conceptualization of learning (Stagl, 2007). Multiple learning types have been distinguished: individual learning, mutual learning (i.e. learning due to the exchange between two parties), or the wider processes of organizational and social learning (Garmendia and Stagl, 2010; Walter et al., 2007). Learning encapsulates improved knowledge and changed behaviors of scenario users, multi-disciplinary and science-society collaborations, or the learning of the scenario developers themselves. No universal definition of the dimensions of learning for scenario analysis exists. In previous research, learning has referred to: improved knowledge and performance in terms of raising awareness; learning from past experiences; of reconsidering the validity of policy assumptions (EEA, 2009); adopting more skilful actions; building new capabilities; listening to the views of others, or searching for solutions that work (Van der Heijden, 2004); promoting dialogue and inquiry; encouraging collaboration and team learning, or empowering people towards collective actions (Chermack et al., 2006); and improving knowledge about the system at hand, the aspired target, and the transformation needed to reach that target (Wiek et al., 2006). This lack of theoretical conceptualization

of learning prevents a systematic development and implementation of frameworks to evaluate the learning success of scenarios.

Many scenario studies claim to lead to learning effects. Multiple conceptual and theoretical evaluations have also argued that using scenarios by definition induces learning about the dynamics of co-evolving human and natural systems and decision options (see [Berkhout et al., 2002](#); [Wiek et al., 2006](#); [Wollenberg et al., 2000](#)). However, there is little empirical evaluative evidence of whether and to what extent these learning effects actually happen ([Trutnevyte et al., 2016](#)). Several recent studies have showed that learning from scenarios may deviate from what scenario developers initially intended ([McMahon et al., 2015](#); [Xexakis and Trutnevyte, 2019](#)). Learning may also only be a short-term response to new information that would fade in the course of several weeks ([Volken et al., 2018](#)), or the scenario users would barely respond to the new scenario information at all ([Bosetti et al., 2017](#)). Empirical evaluation is therefore key to both making any specific scenario analysis effective as well as to improving the scenario methodologies themselves.

In terms of individual learning when scenarios are primarily seen as products, evaluation methodologies from science and risk communication are often used. These methodologies include surveys, interviews, or lab-like experiments. For example, using an experimental survey with university students, [Schoemaker \(1993\)](#) showed that the process of scenario construction for strategically important issues at work or home helps the students expand the range of futures considered. [Chermack et al. \(2006\)](#) used a so-called "Dimensions of the learning organization questionnaire" at an educational institution before and after a scenario planning exercise and showed that scenario planning increases participants' perception of their strategic and communication skills. [Fleishman et al. \(2010\)](#), by means of a survey in workshops, and [Trutnevyte et al. \(2011\)](#), by means of structured interviews, showed that non-experts would adjust their initial views on energy matters after being introduced to long-range future energy scenarios. By means of an online survey about an interactive tool, [Wong-Parodi et al. \(2014\)](#) and [Xexakis and Trutnevyte \(2019\)](#) detected the knowledge gains, consistency of preferences, and active mastery of material by the users of the decision aid.

In terms of group learning when scenarios primarily serve as processes, techniques from evaluating public and stakeholder participation have been adopted for scenario evaluation. For instance, [Stagl \(2006\)](#), [Fleishman et al. \(2010\)](#), [Trutnevyte et al. \(2011\)](#) and [Volken et al. \(2018\)](#) incorporated discussions and surveys in energy scenario development and appraisal processes so they could measure the change in participants' views before and after the scenario exercise. [Walter et al. \(2007\)](#) conducted a survey with participants to evaluate mutual learning in science-society collaboration, based on indicators like the involvement of practitioners (time spent), effects on network building (number of new contacts), trust and understanding of others, community identification, or new knowledge acquired.

In terms of individual and group learning effects when scenarios serve both purposes of products and processes, an interesting example is shown by [Hulme and Dessai \(2008\)](#) who conceptually evaluated the success of four generations of the UK climate scenarios. They attributed two dimensions to learning success: whether the scenarios proved to be engaging and enabled learning. They then operationalized this learning by looking at whether scenarios helped consolidate a community in the public and private sector of actors that use climate change information in their decision making, whether the scenarios stimulated participation of diverse stakeholder groups, what was the actual uptake and usage of the scenarios in the wider debate, as well as what were the self-reported benefits perceived by the scenario users.

4.3. How have scenario processes and scenarios themselves influenced actual decision making?

Many scenario studies aim to inform decision making and thus need to be evaluated as a product or process that contributed to making a

'good' decision. Whether scenarios contributed to the decision success has been a subject of several scenario studies. The question is *what is decision success and how can it be measured?*

Intuitively one might look back and evaluate (in retrospect) whether a decision contributed to its purpose. For example, one could evaluate a flood risk management structure by assessing the amount of flood damage it prevented. However, as argued by [Haasnoot and Middelkoop \(2012\)](#), for many studies the time passed has been too short to decide whether decisions were successful. More importantly, the decision can only be evaluated against a single past (i.e. the actual time since the decision was made), which is only one realisation of the many futures that were possible when the decision was taken. As a result, one could have been fortuitous and evaluate a decision as 'good'. The difficulty of evaluating scenarios against a single past is also addressed by [Van der Duin and Van der Steen \(2012\)](#). They introduce the 'retrospectivity trap': when looking back to futures research in the past, the scenarios are confronted with a detailed past, which may lead to concluding that scenarios are not adequately accurate.

Defining decision success, and finding criteria on how to measure it, is therefore not straightforward ([Hulme and Dessai, 2008](#)). Instead of evaluating whether decisions taken on the basis of a scenario study turned out to be good ones, [Hulme and Dessai \(2008\)](#) defined decision success as whether the scenarios contributed to enabling robust decision making. The justification for this framing comes from the concept of robust decision making ([Groves et al., 2008](#)), which aims to support decisions that are insensitive to poorly characterized deep uncertainties. By including uncertainties in decision making, it is possible to identify strategies that perform relatively well under various different possible futures (robust strategies), or to make a well thought-out decisions on whether or not to adopt a strategy in view of a specific uncertainty. Assessing the robustness of decisions is relevant, because decisions may involve large high-cost investments and can have large implications for society. [Hulme and Dessai \(2008\)](#) addressed decision success with the following question: do the scenarios contain a sufficient representation of relevant knowable uncertainties to offer the prospect that decisions taken with support of the scenarios will be robust? Thus, instead of evaluating the decision against a single past to determine whether it was a good decision, it is evaluated against possible futures.

This line of reasoning was followed by [Haasnoot and Middelkoop \(2012\)](#) who assessed the decision success of six decades of scenario use in national water management studies in the Netherlands with concrete criteria. Whether relevant uncertainties were sufficiently represented was estimated through analysing the range and diversity of the considered scenarios using the following indicators: the number of scenarios, the variety in the range of outcomes encompassed, the variety in alternatives, and the temporal and dynamic nature of the scenarios. They concluded that the possibilities for robust decision making increased through a paradigm shift from predicting to exploring futures, but that the scenario method is not yet fully exploited for decision making under uncertainty. [Trutnevyte et al. \(2016\)](#) suggested that a potential measure of (decision) success could include whether a specific scenario analysis has been followed by any change, such as a policy process, public debate or whether new studies were commissioned.

5. A future research agenda

In this section, we illuminate remaining knowledge gaps and areas where further work is still needed to progress our capability to employ scenario processes and products to aid decision making and learning. [Fig. 3](#) gives an overview on nine avenues of future research which are detailed subsequently. These avenues are sorted according to their focus on either scenarios as *products* or as *processes* and according to the main challenge they focus on, namely *uncertainty* or *complexity*. Uncertainty here refers to the openness of the future; complexity refers to interrelations within and between environmental and societal systems as well as to inter- and transdisciplinarity issues.

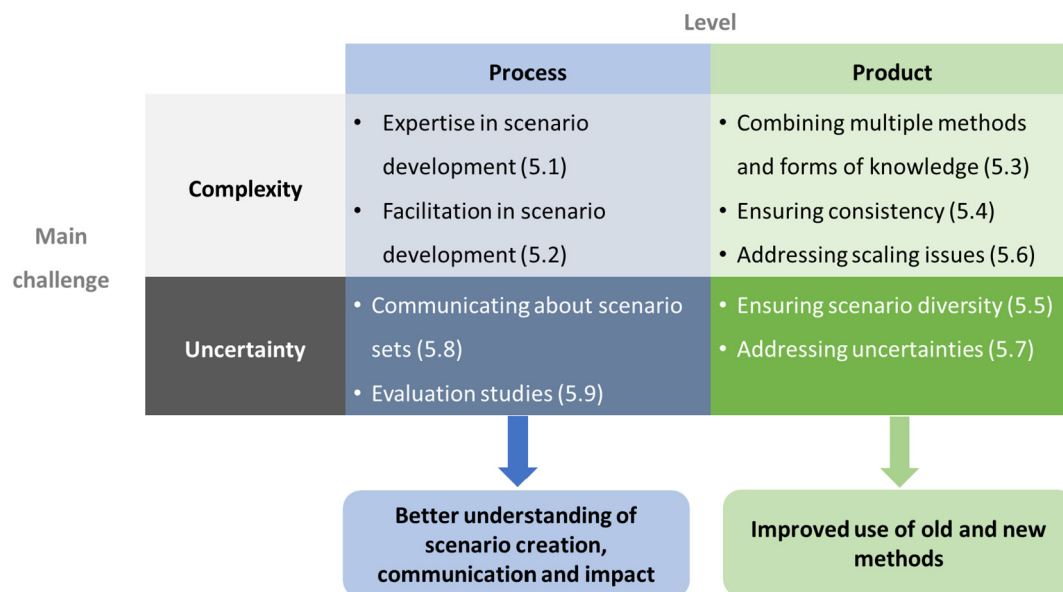


Fig. 3. Overview on future research required to support scenario processes for socio-environmental systems analysis. Numbers refer to the section numbers where the research areas are described.

5.1. Expertise in scenario development

The effective design and implementation of the scenario development process and the quality of the resulting output are contingent on the investigator's experience and knowledge. Yet within the field of socio-environmental studies, there is still limited understanding of what it takes to be a genuine expert in scenario development and how (often tacit, experiential) expertise can be made explicit and be transferred through futures literacy (Miller, 2007; Miller, 2015). We argue that this may hinder the research and practice of scenario development. In particular, we need to know what specific skills and knowledge are required for scenario developers, including:

- How do analytical, foresighting, participatory skills and knowledge elements relate to each other?
- What should a competency framework for learning and teaching scenario development look like?
- What is needed to hone these skills in both formal education and practice settings?

Alternatively, the desired skill sets for performing participatory research with diverse stakeholders, qualitative scenario development, and quantitative modeling are quite different. It may be unrealistic to expect a single person to develop such diverse expertise. Thus, skills for effective collaboration to build, manage and participate in effective teams may be key. More often than not, coordination of a scenario development process requires knowledge brokering skills and the ability to “translate” and communicate between scientific disciplines, research groups, and between scientists and other stakeholders. As scenarios are increasingly being used as boundary objects, the necessary expertise is becoming increasingly transdisciplinary.

5.2. Facilitation in scenario development

As discussed in Section 3.1, effective facilitation activities and skills are as important as the use of robust tools and techniques in the scenario development process. Given the critical role that facilitation plays in influencing the quality of the scenario process and products,

there is a need for more in-depth understanding to unpack the role of facilitators and different facilitation activities (Yearworth and White, 2016), and how they influence the scenario development (i.e. process and product). Most of the evidence on facilitating scenario development is anecdotal. There is a need for systematic review and analysis of the role of facilitation in model-based decision support in general (e.g. Qudrat-Ullah, 2015; Franco and Montibeller, 2010), and scenario development in particular. Some of the open research questions include the following:

- What are the core activities or tasks when facilitating a workshop for scenario development?
- How may these core activities differ depending on the stage of the scenario development process?
- How do different facilitation techniques and practices influence the process dynamics and outcomes?
- What is the role that technology can play in the facilitation process?

5.3. Combining multiple methods and forms of knowledge

Currently, we often deal with the combining of qualitative and quantitative knowledge sources in scenario analysis by ‘muddling through’ approaches (see Section 3.2). To deal with this hybridity more explicitly and in more reflexive ways, firstly we need to develop and use inter- and transdisciplinary procedures and processes that guide us through the challenging tasks of reciprocal expectation management, mutual learning, and trust building between the heterogeneous actors of such endeavours.

Secondly, we need further development of social, technical and cognitive approaches to knowledge integration that bridges different realms and disciplines. One line of research is to develop adequate meta-languages, that is “a language for speaking about knowledge to be integrated and a specification of the integration process” (Hinkel, 2008), like the Unified Modeling Language (UML) in modeling. Another prospective research avenue is leveraging knowledge in cognitive and human behavioural science to support effective scenario development, such as avoiding cognitive biases in foresighting (Winkler and Moser, 2016) and human storytelling abilities (Gaeta et al., 2014). One area

that has not been explored in that regard is computational storytelling techniques (Wang et al., 2016).

Thirdly, we could rethink our established procedures for aligning qualitative and quantitative scenario analysis (see Section 3.2), including the following:

- How can we best combine and iteratively bridge qualitative and quantitative approaches?
- When (or in what cases) is the dominance of models or narratives beneficial?
- When (or in what cases) is the balance of both sides the most productive approach?

Answers to these questions should consider the level of knowledge available (i.e. to pursue the question), and how to make the most use of scientific knowledge and stakeholder knowledge. In addition, we need to consider unresolved issues of presenting and communicating qualitative and quantitative aspects of scenarios separately, before combining them (see Section 3.2).

5.4. Ensuring consistency

On the conceptual front, a more precise definition and use of the term consistency in the scenario community would be helpful to uncover the different meanings, levels and degrees of consistency that are often implicitly mixed up in current discussions, for example internal logical consistency versus consistency as agreement between different qualitative and quantitative (parts of) scenarios. For a first attempt, see Kosow (2015). On the methodological front with regards to the internal logical consistency of scenarios, formal consistency methods exist, but have their limitations as discussed in Section 3.3. Still, we lack a comprehensive and systematic comparison of the different performances of different formal consistency methods as well as guidance for their selection. In addition, many of these approaches rely on pairwise assessments of interactions – open questions include:

- How can scenario consistency studies adequately take into account triangular interactions?
- What role can existing formal consistency methods play to assure not only internal consistency but also consistency between different qualitative and quantitative (parts of) scenarios?
- What new methods do we need to develop to tackle this consistency challenge?

Another issue is the further development of consistency methods in participatory processes. In many cases there is a tension between utilizing more formal and computer-aided methods for qualitative scenario development and stakeholder buy-in (Cash et al., 2003; Voinov and Bousquet, 2010). Addressing this tension depends on the expectations of actors (clients, users, etc.) towards a scenario exercise, and whether the scientific legitimacy gained by more formal methods or the legitimacy gained through engaging stakeholders more deeply and transparently might be more important. The related research question is around:

- How can we develop methodological approaches ensuring legitimacy through both formal methods and through stakeholder inclusion (see Section 3.1)?

Whether the extra effort to ensure consistency is worth it depends on several remaining questions on the empirical front. For example:

- What role does consistency play in the credibility and usability of scenarios, especially for policy making?
- What are the consistency needs for different internal and external users, or for different actor groups like scenario builders, interdisciplinary teams (e.g. social scientists building storylines with stakeholder groups and scientists running a quantitative model) and external scenario users, especially policy makers?
- What are the consistency needs across geographical space and different time horizons (see also Section 5.6)?

5.5. Ensuring scenario diversity

The diversity of scenario sets has been increasingly addressed by the research community. Although the conceptual thinking that scenarios should be distinct from one another has been around for decades, the mathematical formulations have been developed only recently. For working with large ensembles of scenarios in order to extract a smaller set of diverse scenarios, a catalysing effect has been the advent of powerful desktop computers, which has led to the development and application of computationally intensive techniques like exploratory modeling, as well as semi-quantitative methods (Section 3.4). In the future, there is first of all a need to further demonstrate the utility of striving for diversity when developing scenario sets. This paper has highlighted a few examples where diversity measures have been used (see Section 3.4), but this is a very limited set of cases and much work remains to clarify the balance between relatively sophisticated, less transparent mathematical tools and intuitive selection of scenarios of interest with stakeholders. Many scenario processes involve heavy stakeholder engagement, with stakeholder buy-in considered utterly important. Therefore, future research should explore whether simpler and less computationally intensive methods for scenario diversity could be developed, such as a distance-to-selected method (Berntsen and Trutnevyte, 2017). For scenario studies encompassing a limited set of scenarios, another way forward could be to rethink the logic applied in order to make the scenarios distinctive. Attempts to do so include the solution-focused framing applied by O'Neill et al. (2017).

Finally, diversity methods need to be combined with other scenario development and selection approaches. An example which has not been systematically investigated is to combine diversity across scenarios with consistency within scenarios. A potentially interesting research question is whether – and if so, under what condition(s) – there is tension between diversity and consistency. Combining diversity and consistency is not straightforward to address, especially with multiple views on the concepts. OLDFAR (Lord et al., 2016), for example, admits plural measurements of diversity and produces optimized sets robust to those views of diversity. Including plural measurements of consistency, however, would vastly increase the combinatorics behind the diversity optimization.

5.6. Addressing scaling issues

Although most scenarios include processes operating on various spatial and temporal scales, approaches and techniques to deal with scaling issues in scenario exercises seem limited. Existing conceptual papers (e.g. Zurek and Henrichs, 2007; Cash et al., 2006) are often quoted, but recommendations are rarely used beyond the point of acknowledging that they exist. As Schweizer and Kurniawan (2016) argue, there is a need to revisit the concepts of linking scales and attempt to link these with practical scenario development exercises. In addressing spatial scaling issues, research questions can be formulated to develop enhanced approaches for upscaling information from the local or regional scale into scenarios with a higher level of abstraction developed at the national or global level. Similarly, enhanced approaches are needed for downscaling global or national level scenarios, or information from

them, in the development of scenarios at the local scale. Especially challenging is finding approaches that are able to deal with multiple scales within a scenario or approaches that allow for the co-development of scenarios on these different scales. Potentially, lessons could be learnt from the development of integrated assessment models that deal with different spatial scales (e.g. Van Delden et al., 2011).

Addressing time in scenarios involves the choice of a pathway approach or an end-point approach. An open research question is:

- Under what conditions (with respect to scenario users, study participants, scenarios types, development approaches, etc.) are pathway scenarios preferable to endpoint scenarios, and vice versa?

The advantage of a pathway approach is that it allows understanding of the impact of time and the sequence of events, and this concept of temporal dynamics fits well with predictive and exploratory scenarios. However, when using scenario discovery techniques, making use of a pathway approach poses extra challenges as simulating ensembles of multiple time-series of possible futures with a large number of time steps can be computationally expensive. The combination of having detailed scenarios and only a few in number opens pathways to the critique that they may entrench scenario users in limited ways of thinking about the future, thereby leaving them less prepared to confront challenges (Morgan and Keith, 2008). A potential way to deal with this limitation is to develop low-resolution models to enable an exploration of a larger range of uncertainties. When choosing a pathway approach, the issue of temporal scale and resolution becomes pertinent. This requires the need to address the following questions:

- How do processes with short time scales impact on processes with long time scales, and vice versa? How do we deal with events and path dependency within a multi-scale approach?
- What is the impact of the order and speed of developments and events on the scenario results?
- Can integrated models that deal with different temporal scales and resolutions (e.g. Van Delden et al., 2007) assist us in supporting scaling issues in scenario development processes and/or in developing approaches to deal with the scaling challenges posed?

5.7. Addressing uncertainties

Further work is needed on how to deal with both knowable and unknown unknowns in scenario processes. Unknown unknowns or surprises are particularly difficult to address, and more guidance is needed on how to push the boundaries of the state space and better use creativity to approach these types of unknowns. One potential focus is on developing approaches for using surprises as part of a scenario development exercise. A related research area is in the development of quantitative models that are better able to handle or produce surprises and discontinuities. Another research area is in exploring the tensions between scenarios with gradual trends but non-linear changes on the one hand, and surprises, which are non-linear but sometimes have a gradual backstory on the other hand. This latter research area can be tied to the scaling issue challenges (Section 5.6) concerning speed of developments and events, and scales of impact.

As pointed out in Trutnevyte et al. (2016) and Guivarch et al. (2017) one foremost issue that has received little attention to date is evaluation of the methods and tools developed to cope with uncertainty in constructing and selecting scenarios. The issue is about appreciating what the relative strengths and weaknesses of alternative methods are, and in which context each method is best suited.

5.8. Communicating about scenario sets

The key issue in communicating scenarios without ambiguity is to meet the different needs of various user groups and improve co-production of scenarios to increase their usage. Effective communication of scenario outcomes demands simplicity, of which the appropriate selection of scenario indicators plays an important role. One way to achieve simplicity might be through the use of resonant headline indicators as in Levett (1998), whereby each headline indicator is supported by a pyramid of more technical indicators. While some effort has been directed to improving communication of scenarios through the development of sophisticated tools, such as interactive web-tools, a recent study has shown that such tools can in fact result in poorer understanding of scenarios by participants compared to communication using storylines (Xexakis and Trutnevyte, 2019). These findings highlight the need for pragmatic approaches to communication that meet the needs of users. This research area would definitely benefit from more empirical evaluations on the effectiveness of communication and visualization techniques.

A critical point linked to evaluation is the need for better understanding of the impacts of inappropriate selection of scenarios.

- If a set of scenarios is too conservative, unbalanced, too large, or has missed crucial uncertainties, what impacts does that have on practice?
- Did it favour or disfavour a specific type of decision, or a particular group of stakeholders?
- How can scenarios studies cope with these issues?

Another set of questions relate to the communication of scenarios to a diverse group of users.

- How do we best communicate complex scenarios and many scenarios to a diversity of users?
- In particular, how do we effectively communicate to those not involved in the co-production of the scenarios or to people not used to working in transdisciplinary areas?

5.9. Evaluation studies

Instead of assuming that there will be individual and group learning effects, scenario developers should always set up a process for gathering empirical evaluative evidence. That is, scenario analysis should not stop after producing scenarios, but continue with evaluation (Trutnevyte et al., 2016; Xexakis et al., 2019). As learning effects are complex and at times unexpected, basic research is still needed on the appropriate nature of these evaluation processes and on what kind of evaluation methods should be applied (Section 4.2). As the amount of evaluative evidence and methods grows, a theoretical, unifying framework should ideally be developed and operationalized. This theoretical framework could, for example, be developed based on the state of the art in science and risk communication (Fischhoff, 2013; Pidgeon and Fischhoff, 2011), as well as from less-explored evaluations of public and stakeholder engagement processes for evaluating group learning. Intriguingly, as scenario analyses cross multiple elements of individual and group learning, this new theoretical framework will be multi-dimensional and interdisciplinary, and may explore a range of criteria. Advances in the related socio-environmental systems analysis literature can provide a useful foundation to build on. For example, Hamilton et al. (2019) offered a multi-dimensional definition of success for socio-environmental modeling and decision analysis exercises and characterized success according to the intervention's level of impact (project, individual, group, system) and the expected timeframe for outcomes to become apparent. On a parallel track, overarching, independently conducted studies on

evaluating learning effects could further facilitate learning from comparative evaluations of many scenario exercises.

6. Conclusions

This paper has given an overview of the challenges facing researchers and practitioners when using scenario processes and products for socio-environmental systems (SES) analysis and model-based decision support. These challenges address both the process of scenario analysis and the actual products, that is how it is undertaken and the scenarios themselves. The key challenges with respect to SES in particular include: enhancing the role of stakeholder and public engagement in the co-development of scenarios, linking scenarios across multiple geographical and temporal scales, improving the links between the qualitative and quantitative aspects of scenario analysis, addressing surprise, communicating scenarios, and linking scenarios to decision making. Fruitful research areas to improve the development and use of scenario processes should not exclude explicit understanding of the skills and competencies required for scenario development. Core methodological developments are still needed to ensure scenario diversity, consistency, and to improve the way scenario processes deal with uncertainty. As a synthesis of the state-of-the-art in scenario processes, this paper intends to help advance scenario methodology and practice in socio-environmental systems analysis. Given the critical uncertainties we as society face about the environment, scenario analysis is a promising approach to broaden and deepen our thinking about the future and thereby for improving planning and decision making.

CRedit authorship contribution statement

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Declaration of competing interest

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