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Research article

A protocol to develop Shared Socio-economic Pathways for European agriculture

Hermine Mitter [a,*], Anja-K. Techen [b], Franz Sinabell [c], Katharina Helming [b], Kasper Kok [d], Jörg A. Priess [e], Erwin Schmid [a], Benjamin L. Bodirsky [f], Ian Holman [g], Heikki Lehtonen [h], Adrian Leip [i], Chantal Le Mouël [j], Erik Mathijs [k], Bano Mehdi [l], Melania Michetti [m], Klaus Mittenzwei [n], Olivier Mora [o], Lillian Øygarden [n], Pytrik Reidsma [p], Rüdiger Schaldach [q], Martin Schönhart [a]

[a] University of Natural Resources and Life Sciences Vienna, BOKU, Institute for Sustainable Economic Development, Austria
[b] Leibniz Centre for Agricultural Landscape Research, ZALF, Germany
[c] Austrian Institute of Economic Research, WIFO, Austria
[d] Wageningen University, WUR, Soil Geography and Landscape Group, the Netherlands
[e] Helmholtz-Centre for Environmental Research, UFZ, Germany
[f] Potsdam Institute for Climate Impact Research, PIK, Germany
[g] Cranfield University, UK
[h] Natural Resources Institute Finland, LUKE, Finland
[i] European Commission, Joint Research Centre, Ispra (VA), Italy
[j] UMR 1302 SMART-LERECO, Institut National de la Recherche Agronomique, INRA, Rennes, France
[k] University of Leuven, KU Leuven, Division of Bioeconomics, Belgium
[l] University of Natural Resources and Life Sciences Vienna, BOKU, Division of Agronomy, Austria
[m] Fondazione Centro Euro-Mediterraneo Sui Cambiamenti Climatici, CMCC, Italy
[n] Norwegian Institute of Bioeconomy Research, NIBIO, Norway
[o] UAR 1241 DEPE, Institut National de la Recherche Agronomique, INRA, Paris, France
[p] Wageningen University, WUR, Plant Production Systems Group, the Netherlands
[q] University of Kassel, Germany

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ABSTRACT

Moving towards a more sustainable future requires concerted actions, particularly in the context of global climate change. Integrated assessments of agricultural systems (IAAS) are considered valuable tools to provide sound information for policy and decision-making. IAAS use storylines to define socio-economic and environmental framework assumptions. While a set of qualitative global storylines, known as the Shared Socio-economic Pathways (SSPs), is available to inform integrated assessments at large scales, their spatial resolution and scope is insufficient for regional studies in agriculture. We present a protocol to operationalize the development of Shared Socio-economic Pathways for European agriculture – Eur-Agri-SSPs – to support IAAS. The proposed design of the storyline development process is based on six quality criteria: plausibility, vertical and horizontal consistency, salience, legitimacy, richness and creativity. Trade-offs between these criteria may occur. The process is science-driven and iterative to enhance plausibility and horizontal consistency. A nested approach is suggested to link storylines across scales while maintaining vertical consistency. Plausibility, legitimacy, salience, richness and creativity shall be stimulated in a participatory and interdisciplinary storyline development process. The quality criteria and process design requirements are combined in the protocol to increase conceptual and methodological transparency. The protocol specifies nine working steps. For each step, suitable methods are proposed and the intended level and format of stakeholder engagement are discussed. A key methodological challenge is to link global SSPs with regional perspectives provided by the stakeholders, while maintaining vertical consistency and stakeholder buy-in. We conclude that the protocol facilitates systematic development

* Corresponding author. University of Natural Resources and Life Sciences Vienna, Institute for Sustainable Economic Development, Feistmantelstrasse 4, 1180, Vienna, Austria.
E-mail address: hermine.mitter@boku.ac.at (H. Mitter).

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and evaluation of storylines, which can be transferred to other regions, sectors and scales and supports inter-comparisons of IAAS.

1. Introduction

Agriculture is exposed to considerable challenges posed by changes in climate, environment, demography, policy, technology, consumer preferences and trade. Farmers, agricultural policy makers, decision makers in international organizations, and supply chain managers need evidence and guidance to respond to these challenges and take informed decisions (Bruno Soares et al., 2018; Haigh et al., 2018; Hewitt et al., 2012). Enhancing the understanding of social environmental systems and their dynamics is key in order to sustainably manage agricultural and natural resources, to effectively utilize synergies and to gradually reduce trade-offs (Messerli et al., 2019).

Integrated assessments of agricultural systems (IAAS), which can be defined as a structured, quantitative approach combining theories, data and methods from different disciplines to describe, explain and explore cause-effect relationships, can improve system understanding and provide useful information to design policies and guide land use management decisions (Hisschemöller et al., 2001; Laniak et al., 2013; Rotmans and Asselt, 2001; van Ittersum et al., 2008). IAAS have been applied at various spatial scales to analyze potential changes in land cover and land use due to changes in climatic, environmental and socio-economic conditions (Helming et al., 2011; Holman et al., 2017; Michetti and Zampieri, 2014; Mitter et al., 2015b; Popp et al., 2017; Schaldach et al., 2011), to quantify the effect of changes in land use management on environmental indicators such as water quality, soil erosion, greenhouse gas emissions and biodiversity (Gutzler et al., 2015; Kirchner et al., 2015; Mehdi et al., 2015; Mitter et al., 2014; Popp et al., 2017; Priess et al., 2011; Reidsma et al., 2015a; Schaldach et al., 2018; Schönhart et al., 2018), and to identify effective agricultural adaptation measures and their potential environmental impacts (Mitter et al., 2015a; Reidsma et al., 2015b). Ex-ante integrated assessments require scenarios, i.e. plausible, internally consistent, and recognizable sequences of events over a future period of time (Boschetti et al., 2016; Hunt et al., 2012; IPCC, 2014; Rotmans et al., 2000). Scenarios can be qualitative 'storylines' (also referred to as narratives), quantified descriptions of future pathways, or anything in between (Reed et al., 2013; Swart et al., 2004), and can serve as input to IAAS (Pedde et al., 2018; Rotmans and Asselt, 2001). Their scope depends on system boundaries, exogenous drivers, and endogenous response structures. Scenarios can also be useful to challenge stakeholder discussions on potential regional development pathways, to increase understanding on cause-effect relationships in social environmental systems, and to inform strategy development (Wright et al., 2013).

Researchers working on climate change have developed a set of storylines, i.e. the 'Shared Socio-economic Pathways' (SSPs, Kriegler et al., 2012), to inform integrated assessments at large spatial scales. The SSPs are available at global (O'Neill et al., 2017, 2014) and European scales (Eur-SSPs; Kok et al., 2018). They have been developed to be linked to the Representative Concentration Pathways for climate change modeling (RCPs, Moss et al., 2010). The SSPs qualitatively describe five contrasting socio-economic pathways into the future and refer to technological and environmental elements. They are organized along two gradients of socio-economic challenges for climate change mitigation and adaptation (O'Neill et al., 2017, 2014), but do not explicitly describe mitigation and adaptation efforts. The five pathways include: a world with great emphasis on sustainability and equality with low challenges to mitigation and adaptation (SSP1); a 'middle of the road' world in which socio-economic and technological development follows historical trends and challenges to mitigation and adaptation are medium (SSP2); a fragmented world in which nationalism resurges and challenges to mitigation and adaptation are high (SSP3); a world characterized by increasing inequality with low challenges to mitigation and high challenges to adaptation (SSP4); and a world with rapid technological progress and economic growth strongly relying on fossil fuels with high challenges to mitigation and low challenges to adaptation (SSP5).

SSPs touch upon important elements affecting agricultural emissions, environmental policies, the demand for and supply of agricultural products and services (Popp et al., 2017), but remain non-exhaustive. Due to their global coverage, they do not sufficiently account for supra-national policy agendas nor for national or sub-national sectorial characteristics. Such information is, however, key to perform IAAS and investigate potential future developments of the agricultural sector and its impacts on the environment within the RCP-SSP framework at national and sub-national scales. The mismatch in spatial scale and the insufficient representation of necessary elements can be managed by enriching SSPs according to the needs of IAAS. Several concepts and procedures have been discussed to interpret global storylines at a smaller spatial scale or to include details for particular sectors (Biggs et al., 2007; Zurek and Henrichs, 2007). For instance, Alcamo (2001) and Bertrand et al. (1999) propose two linked stages of scenario development resulting in two independent products, i.e. cross-cutting 'global' and theme-specific 'partial' scenarios, to broaden the scope. Related to SSPs, Kok et al. (2018) suggest to map existing scenarios at different scales in a systematic manner to benefit from previous research and participatory work. O'Neill et al. (2014) recommend distinguishing between 'basic' and 'extended' SSPs, whereby extended SSPs are meant to build on the basic SSPs and provide more details to support national, sub-national, or sectoral analyses. Following this concept, Biewald (2016) proposes extended SSPs for European agriculture and identifies key elements for IAAS that are missing or are insufficiently described in the SSPs including, for instance, European agricultural policy. Rosenzweig et al. (2013) and Valdivia et al. (2015) have developed the concept of Representative Agricultural Pathways (RAPs) to link global RCPs and SSPs with the needs of national and regional IAAS. They suggest reframing the scenario matrix by using geo-biophysical and socio-economic indicators as contextual factors. Mathijs et al. (2018) provide explorative storylines for the food sector in the European Union with a particular focus on consumer trends. Their storylines are based on the SSPs and are complemented with information from existing scenarios on specific topics (e.g. food safety and nutrition) and expert knowledge. All these efforts form a solid basis but are limited in their applicability for IAAS. They either stay at the conceptual level (Alcamo, 2001; Bertrand et al., 1999; O'Neill et al., 2014), are not consistent with the SSPs (Rosenzweig et al., 2013; Valdivia et al., 2015), or do not provide sufficient details with respect to the geo-biophysical, socio-economic and technological elements of agriculture required in IAAS (Biewald, 2016; Kok et al., 2018; Mathijs et al., 2018; O'Neill et al., 2014).

So far, researchers have typically developed scenarios for individual analyses or spatial units, often in cooperation with stakeholders and tailored to the needs of particular models (e.g. Mehdi et al., 2018; Priess and Hauck, 2014; Schönhart et al., 2018). Recent activities have also considered the global SSPs for national or sub-national analyses (see e.g. Frame et al., 2018; Nilsson et al., 2017; Reimann et al., 2018; Willaarts et al., 2019). However, experience shows that this co-production practice is resource intensive for researchers and stakeholders (Polk, 2015) and often leads to discontinuous stakeholder engagement (Lang et al., 2012) and consultation fatigue (Reed, 2008). Furthermore, it has resulted in a myriad of storylines that aggravate comparisons of IAAS and thus confuse policy and decision-makers. The development of Shared Socio-economic Pathways for European agriculture

(Eur-Agri-SSPs) aims to provide a common framework for operationalizing global SSPs for the European agricultural sector. Thereby, they should reduce misunderstandings and potentially conflicting interpretations of SSPs for sub-European or sub-sectoral analyses and provide a common basis for IAAS and the identification of effective and efficient mitigation and adaptation measures. Climate change mitigation and adaptation are key to the environmental performance of agricultural systems with substantial trade-offs and synergies between alternative management measures (Kirchner et al., 2015; Mitter et al., 2018). Hence, the Eur-Agri-SSPs can become an important component of regional to local ex-ante environmental assessments in Europe.

Here, we present a protocol as a methodology to extend and enrich global SSPs and derive Eur-Agri-SSPs. We build on the approaches suggested in the literature, while overcoming the above mentioned barriers. The protocol contributes to enhance conceptual and methodological transparency and rigor as well as scientific credibility of storyline development (Carlsen et al., 2017) by combining storyline quality criteria and process design requirements. It helps to make storyline-based IAAS more systematic and to improve interpretation and comparability of research results (Ruane et al., 2017). Transferability of the protocol is key to allow researchers with similar needs and facing similar challenges to adapt it with minor modifications. Therefore, while the protocol is designed to guide the development of Eur-Agri-SSPs and increase reproducibility, it is meant to remain generic and flexible enough to allow for its use at differing continental, national, sub-national, or sectoral scales.

We address two major research questions: (i) which quality criteria should Eur-Agri-SSPs satisfy to form the basis of IAAS at various spatial scales? and (ii) how can a typical development process, i.e. protocol, be conducted to obtain storylines that are consistent with the global SSPs and relevant to scientists and stakeholders?

The article is structured as follows: in section 2, we describe the methodology for developing a protocol; section 3 introduces the working steps of the protocol; in section 4, challenges of the storyline development process are discussed; and in section 5, conclusions are drawn.

2. Methodology to develop a protocol

2.1. Team and process

A diverse group of scientists has developed a protocol for extending SSPs and developing Eur-Agri-SSPs to support IAAS. The workflow was organized in several steps and responsibilities were distributed amongst different members of the scientific team. A **core group** consisting of six scientists with multiple disciplinary backgrounds conducted a literature review on widely acknowledged standards and methodologies for storyline development and incremental procedures (e.g. Alcamo, 2008, 2001; O'Brien, 2004; Priess and Hauck, 2014; Priess et al., 2018; Rose and Star, 2013; Rosenzweig et al., 2016; Rounsevell and Metzger, 2010). The literature review served as a basis for defining quality criteria of Eur-Agri-SSPs and closely related process design requirements (see section 2.2). Both quality criteria and process design requirements supported structuring the newly developed protocol (see section 3). An internal review process involving scientists from 17 universities and research institutes across Europe (i.e. supporting **group**) aimed to ensure that the protocol meets widely accepted storyline development standards, satisfies the requirements of IAAS and, at the same time, is sufficiently flexible for its application at various scales and (sub-)sectors. Further details on the team and the process are provided in the Supplementary data 1 and 2.

The development of Eur-Agri-SSPs to support IAAS may be understood as both 'process' and 'product' (Hulme and Dessai, 2008). The first refers to the development steps that need to be taken and the actors involved and the second to the final storylines that can be used in research, agricultural and environmental policy and decision making. Based on the literature, we define process design requirements as well as quality criteria for the product, i.e. the storylines (Tables 1 and 2).

2.2. Storyline product quality criteria

The **product criteria** are based on acknowledged guidelines for evaluating storylines (Alcamo and Henrichs, 2008; Cash et al., 2003; Rounsevell and Metzger, 2010) and comprise plausibility, consistency, salience, legitimacy, richness and creativity. The product criteria as well as suggestions for their operationalization and interpretation are summarized in Table 1. **Plausibility** refers to the futures that could happen according to our current knowledge and, thus, the images conveyed as well as the causality and recognizability of underlying assumptions (Alcamo and Henrichs, 2008; Voros, 2003). **Consistency** can be classified into vertical and horizontal. Vertical consistency refers to a 'soft link' of storyline elements across spatial scales meaning that larger scale storylines (such as the global SSPs) provide boundary conditions for smaller scale storylines. Such boundary conditions inform, for instance, major storyline assumptions, the selection of storyline elements and their trends (Zurek and Henrichs, 2007). Horizontal consistency specifies the internal logic of a storyline and addresses inter-sectoral consistency, e.g. between crop and livestock sectors. **Salience** relates to the relevance of storylines for targeted users (including scientists and non-scientists) by addressing their needs and concerns (Alcamo and Henrichs, 2008; Cash et al., 2003). **Legitimacy** points to transparency, participation and fairness in storyline development and ensures that the storylines are respectful of diverse interests, preferences, and

Table 1
Quality criteria of storylines and suggestions for their operationalization.

Quality criteria	Operationalization
Plausibility	The storylines present plausible views of the future. The storylines are recognizable in the present. The causalities described in the storylines are reasonable and potential future disruptions are considered.
Consistency (vertical and horizontal)	The smaller scale storylines increase spatial and thematic resolution. Scaling introduces additional information, which is particularly relevant to actors and storyline users at smaller scales. The storylines respect boundary conditions from larger scale storylines. The storylines allow for thematic specification. The storylines allow for spatial specification. The storylines are internally consistent.
Salience	The storylines are clear (accurate verbalization) and comprehensible. The storylines are accessible to targeted users. The storylines can inform the field of duties of targeted users.
Legitimacy	Scientific, experiential and bureaucratic knowledge represented by persons with multiple backgrounds is integrated in the storylines.
Richness	The storylines provide a comprehensive picture of potential future developments. Multiple geo-biophysical, socio-economic and technological drivers affecting the system of interest are addressed in the storylines. The storylines allow mitigation and adaptation challenges to be deduced. The storylines provide generic assumptions, which can inform further specifications.
Creativity	The storylines are significantly different from each other, i.e. they are sufficiently contrasted. The storylines provoke visionary thinking and incorporate potential feedbacks and surprises. The storylines address the wide range of plausible futures.

Note: The operationalization of the quality criteria was informed by Alcamo and Henrichs (2008), Girod et al. (2009), and Priess and Hauck (2014).

worldviews (Cash et al., 2003; Girod et al., 2009; Rounsevell and Metzger, 2010). **Richness** refers to the comprehensiveness, and the level of detail of a set of storylines (Alcamo, 2008). **Creativity** refers to the difference between, and diversity of, storylines. Hence, they do not only cover current trends but also consider weak signals, non-linear and surprising developments, uncertainties as well as a plurality of visions and perspectives and thus challenge current beliefs and views about the future (Alcamo and Henrichs, 2008; Rotmans et al., 2000; Tietje, 2005).

Previous analyses have shown that quality criteria for storylines are tightly coupled suggesting that synergies and trade-offs may occur (Cash et al., 2003; Rounsevell and Metzger, 2010). For instance, 'rich' storylines that address multiple future drivers are likely to consider different interests and worldviews, i.e. legitimate. High vertical consistency may reduce creativity and salience for policy and decision makers and, thus, stakeholder buy-in (Zurek and Henrichs, 2007).

2.3. Process design requirements

The **design of the storyline development process** is closely related to the quality criteria. For instance, a science-driven process is proposed in order to enhance plausibility. **Science-driven** means that any assumptions made are scientifically corroborated. Scientists plan, conduct, document and evaluate major steps, and choose scientifically adequate methods. An iterative process shall increase vertical and horizontal consistency of the storylines. **Iterative** refers to a systematic and repetitive process, which is characterized by sequential action and reflection. Internal and external feedback loops are introduced in critical steps of the process and documented for reasons of quality control. A **top down** approach has been recommended to translate storylines from larger to smaller spatial scales while maintaining vertical consistency (Biggs et al., 2007). Absar and Preston (2015) differentiate between downscaling and nesting approaches, whereby downscaling refers to the generation of quantitative scenario elements with smaller spatial resolution than the original data source (Abildtrup et al., 2006; van Vuuren et al., 2010, 2007). **Nesting** implies that qualitative storylines are enriched at increasingly smaller scales. Further information on the top-down, nested approach is given in the Supplementary data 3.

Table 2
Process design requirements and suggestions for their operationalization.

Process design requirements	Operationalization
Science-driven	The storyline development process is systematically planned, carefully documented and evaluated. State-of-the-art methods are applied, and their strengths and weaknesses are discussed. Assumptions in the storylines are in accordance with the literature and made explicit.
Iterative	Reviews and feedback loops are (i) introduced at critical steps of the storyline development process, and (ii) repeated until an acceptable result of the working step(s) is achieved.
Top down, nested	Storylines at large spatial scales represent boundary conditions for storylines at smaller scale, and potential deviations are justified. Storylines at large spatial scale specify major storyline assumptions, storyline elements, and development trajectories.
Consecutive	Storylines at large spatial scale are finalized and serve as a basis for developing smaller scale storylines. Storylines at smaller spatial scale do not feed back to large scale storylines.
Participatory	There is a broad and balanced engagement of scientific and non-scientific actors for developing storylines. Inputs from all actors (e.g. interests, perceptions, needs and concerns) involved are treated openly and unbiasedly. The storyline development process encourages creative thinking.
Interdisciplinary	An interdisciplinary team is coordinating the storyline development process.

Note: The operationalization of the process design requirements was informed by Alcamo and Henrichs (2008) and Girod et al. (2009).

Consecutive refers to the timing of storyline development suggesting that storylines are first finalized at one spatial scale before storylines at another spatial scale are designed, while the original ones remain unaltered (Zurek and Henrichs, 2007). A consecutive development is reasonable because global SSPs have been published (O'Neill et al., 2017), their structure meets current demands of the research community and selected storyline elements have already been quantified (e.g. change in global demand for crops and livestock products; Popp et al., 2017) and can inform the new Eur-Agri-SSPs. Furthermore, developing global and European storylines iteratively (in contrast to consecutively) would be very demanding due to the complexity and interactions of global and European processes. A consecutive development of global SSPs and Eur-Agri-SSPs facilitates achieving vertical consistency (Kok et al., 2018). A **participatory** and interdisciplinary process should be set up to increase salience, legitimacy, richness, and creativity. A participatory process focuses on co-production of knowledge through partnerships between scientists and stakeholders, i.e. people affected by or responsible for action on the issues under study (Cornwall and Jewkes, 1995; Jagosh et al., 2012). A broad, balanced, and professional engagement of stakeholders stimulates discussion and helps to address their interests, preferences, needs, and concerns as well as on-going projects and professional activities. **Interdisciplinary** refers to the cooperation of scientists from at least two disciplines who aim at integrating their insights and modes of thinking to acquire a more comprehensive understanding (Defila and Di Giulio, 1999; Repko et al., 2016). Interdisciplinary cooperation is key such that various aspects of the agricultural and related human environment systems can be thoroughly discussed, and the final storylines meet the needs of scientists applying different methods to answer new research questions. The process design requirements as well as suggestions for their operationalization and interpretation are summarized in Table 2.

3. Protocol to develop Shared Socio-economic Pathways for European agriculture (Eur-Agri-SSPs)

The protocol consists of **nine major working steps** for developing Eur-Agri-SSPs (Fig. 1). The working steps build on widely accepted standards for storyline development and documented experience from previous storyline development processes (e.g. Alcamo, 2008, 2001; O'Brien, 2004; Priess and Hauck, 2014; Priess et al., 2018; Rose and Star, 2013; Rosenzweig et al., 2016; Rounsevell and Metzger, 2010). They have been adapted such that the Eur-Agri-SSPs respond to the needs of IAAS, deepen the understanding of the interlinkages between social and environmental changes and related synergies and trade-offs.

The working steps are described in more detail in the following subsections. Each sub-section explains the aim of a particular working step, refers to the storyline product quality criteria (section 2.2) and the process design requirements (section 2.3); defines key responsibilities in the team for conducting the work; suggests levels of stakeholder engagement; and provides a selection of methods that can be used to achieve the aims of the respective working step. Where applicable, indications are given as to how the steps have been operationalized in order to develop the Eur-Agri-SSPs.

The working steps are designed to be transferable to other sectors and scales and the defined storylines should finally help to illustrate potential future developments of social environmental systems, to address environmental problems and to identify sustainable management options.

3.1. Defining key characteristics of the storylines

The key characteristics of the storylines need to be clearly defined in the first working step. The process may be science- or stakeholder-driven, i.e. driven by interests and information needs of researchers or

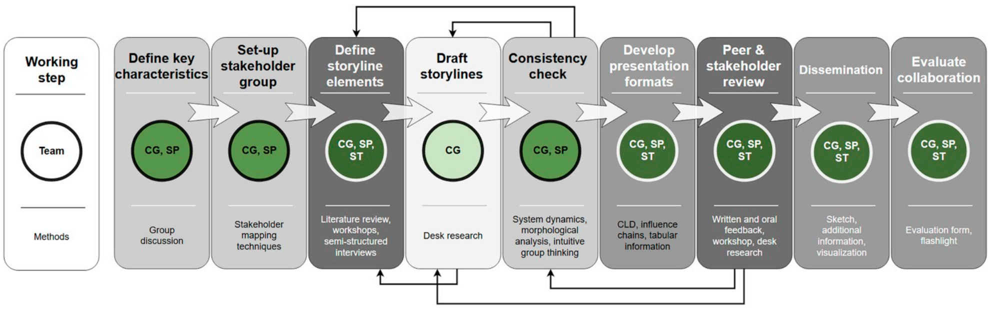

Fig. 1. Overview of the protocol for developing Eur-Agri-SSPs. Notes: The protocol consists of nine major working steps, as indicated by the rectangles and the broad arrows. The thin arrows indicate that the process design is iterative and that some working steps need to be repeated until final storylines are available. The team who develops the protocol and the Eur-Agri-SSPs consists of three working groups: CG = Core group; SP = Supporting group; ST = Stakeholder group. The responsibilities differ by working steps and are presented in the circles. Color intensity in the circles (shade of green) indicates the involved working groups. The more working groups involved, the darker the color. Color intensity in the rectangles (shade of grey) indicates the suggested level of stakeholder engagement ranging from level 0 to level 3. The higher the suggested level of stakeholder engagement, the darker the color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

stakeholders (Henrichs et al., 2010). The key characteristics include the major goal and purpose of the storylines, main target groups, thematic foci, spatial and time scales as well as the type of storylines. Clarity about the goal, purpose and targeted users helps to define thematic foci, spatial and temporal scales that serve the interests of the main target groups in order to ensure **salience.** Furthermore, they are a crucial prerequisite for **specifying the protocol-driven process**.

Key characteristics of the Eur-Agri-SSPs are specified below because they influence further steps of the protocol. The core and supporting groups have been involved in defining the key characteristics of the new storylines, i.e. science-driven. Collaboration between the core and supporting groups is reasonable for this step in the case of the Eur-Agri-SSPs, because they are responsible for initiating and coordinating the process and represent the main target group of the new storylines. Moderated group discussions, which can take place virtually, e.g. via video conference, or in person, have proven to be appropriate to achieve the targets of this working step.

Goal and purpose. The major goal of developing Eur-Agri-SSPs is to extend the SSPs and Eur-SSPs such that they provide the required information to perform IAAS. Furthermore, Eur-Agri-SSPs aim to stimulate research, agri-environmental and climate policy ideas, education and training as well as communication and discussion among stakeholders. The major purpose of developing Eur-Agri-SSPs is closely related to the major goal. The Eur-Agri-SSPs should increase comparability of results from IAAS across sectors and spatial scales and save research resources and stakeholder endeavor through cooperation and collaboration.

Target groups. The main target group of the new storylines are scientists working on climate change, environmental protection or integrated assessments who are interested in providing research results that are useful for scientific and non-scientific actors. Additionally, the Eur-Agri-SSPs should inform supply chain managers as well as European policy and decision makers working on agricultural or environmental issues.

Thematic foci, spatial and time scales. We define system boundaries in terms of thematic foci, spatial scale, and time horizon of the Eur-Agri-SSPs according to the interests and needs of the main target groups. The Eur-Agri-SSPs thematically focus on potential developments of European agriculture in the next decades. In particular, they describe which geo-biophysical, socio-economic, and technological conditions will potentially affect farm structure, land cover, land use, and agricultural production and how various actors in the agricultural supply chain (including suppliers of inputs, farmers, food and feed industries) are interrelated. Related sectors such as forestry, energy, water or natural resource extraction are considered if they directly affect agricultural development. The spatial scale of the Eur-Agri-SSPs is Europe, with differentiation between nations or agri-environmental zones kept at a minimum level. Links to other parts of the world are only considered for specific drivers of future development such as international trade. With respect to the time horizon, the Eur-Agri-SSPs focus on the next three decades, i.e. until 2050. Even though the SSPs cover the period until 2100, the first half of the 21st century is chosen for the Eur-Agri-SSPs. This time period has been successfully addressed in previous stakeholder collaborations, and coincides with several policy objectives of the European Union (e.g. European Commission, 2011) and other storyline and scenario exercises (e.g. Gramberger et al., 2011; Mylona et al., 2016; Vervoort et al., 2016).

Type of storylines. We design the Eur-Agri-SSPs as **problem-focused** and **qualitative** storylines. Problem-focused storylines emphasize and explore drivers and their interactions that shape future developments (Henrichs et al., 2010). The Eur-Agri-SSPs shall focus on drivers of the European agricultural sector that are given priority by scientists and non-scientists and are deemed to be highly uncertain in the future. It is about balancing richness and salience for subsequent IAAS and non-quantitative applications by stakeholders. Qualitative refers to the text-based and graphical presentation format, which allows to highlight relationships between drivers and the dynamics of their evolution (Alcamo, 2008; IPCC, 2014; Rotmans et al., 2000).

3.2. Establishing a team and setting-up a stakeholder group

Developing storylines that meet the quality criteria, being adopted by integrated assessment researchers and accepted by stakeholders, implies to integrate experts with different academic and non-academic backgrounds and professional knowledge and expertise in the process.

Therefore, the second step deals with establishing a storyline development team, whereby the role of stakeholders is key and effort needs to be devoted to stakeholder identification, categorization and exploring relationships between stakeholders. Engaging a broad variety of stakeholders in a storyline development process has been suggested to increase **salience, horizontal consistency, richness and creativity** of the storylines (Alcamo and Henrichs, 2008). It is crucial in order to ensure coverage of relevant storyline elements and potential directions of change, internal logic of storylines as well as widespread adoption of the storylines (Kriegler et al., 2012; Reed et al., 2013). A balanced representation of different stakeholder groups, as well as professional facilitation in stakeholder engagement activities, helps to reduce tensions between potentially opposing interests, preferences, disciplinary approaches and worldviews and thus to increase **legitimacy** and decrease bias (Ernst et al., 2018; Garard and Kowarsch, 2017).

A variety of methods exists for identifying, categorizing and exploring relationships between stakeholders. Stakeholder **identification** can, for instance, be informed by literature and document analysis as well as via professional networks. It can also take place via asking gatekeepers and by applying the snowball sampling approach (Biernacki and Waldorf, 1981). A combination of the suggested methods is recommended. Defining criteria for stakeholder **categorization** is necessary to reach and obtain a diversity of people. Suggestions for potential criteria have been given by Alcamo and Henrichs (2008) and can address the need to integrate stakeholders with a wide spectrum of knowledge types (see e.g. Raymond et al., 2010), interests and topical expertise, academic and non-academic backgrounds, roles in policy- and decision-making, nationalities, cultures, gender and age. Analytical techniques can be applied to identify stakeholders with similar interests, concerns, and power to **explore relationships between stakeholders.** Examples include an interest-influence matrix, rainbow diagram, actor linkage matrix or social network analysis. An overview of established methods, their field of application and strengths and weaknesses is presented, for instance, in Durham et al. (2014) and in Reed et al. (2009).

For developing Eur-Agri-SSPs, we have established three working groups, i.e. **core group,** supporting **group, and stakeholder group**, with varying interests, backgrounds and responsibilities (Table 3). Differentiating between working groups with specific tasks has proven effective in previous storyline and scenario exercises (see e.g. Alcamo and Henrichs, 2008; Le Mouël et al., 2018; Rose and Star, 2013). Furthermore, it may be beneficial to consider more than one stakeholder group in storyline development processes (see e.g. Bergez et al., 2011; Mitter et al., 2014; Priess and Hauck, 2014).

The core and supporting groups should contribute to setting-up a stakeholder group because actors from both groups can provide access to diverse stakeholders. Even though a large number of stakeholders may be interested in storyline development or provide relevant insights, stakeholder engagement should follow a coherent strategy in order to reach defined goals and, at the same time, avoid consultation fatigue.

Therefore, we distinguish between **four levels of stakeholder engagement,** defined by (i) the number and heterogeneity of persons contributing to the storyline development process, (ii) the degree of interaction, and (iii) the preferred format of stakeholder engagement (Table 4). A high level of stakeholder engagement is characterized by integrating a large number of persons with diverse perspectives, interests, experiences, knowledge and skills. The degree of interaction may vary between information, consultation, and collaboration (Durham et al., 2014; Krütli et al., 2010; Wiek, 2007). Information is characterized by a unidirectional information flow between the core, supporting and stakeholder groups. Consultation can be a bi- or multi-directional exchange of ideas, perceptions and information. Collaboration occurs when members from the supporting and stakeholder groups contribute with data or resources, and co-determine the research direction and process. The level of engagement needs to be adjusted to the aim and timing of the respective activity and requires an adequate format. In most working steps, information and consultation may be adequate. However, collaboration may be desirable in critical phases of the research process.

The boundaries between the four levels of stakeholder engagement may be blurred. For instance, scientists contributing to the storyline development process in the supporting group (Level 1) may sometimes act as 'scientific stakeholders' (Level 2-3). Even though a high level of stakeholder engagement may be desirable in several phases of the storyline development process, resource constraints by members of the core, supporting, and stakeholder groups may limit the level of stakeholder engagement, the number of contributors or the scope of their backgrounds.

Table 3
Characteristics of the three working groups developing the Eur-Agri-SSPs.

	Stakeholder group	Supporting group	Core group
Actors	Non-scientific (e.g. representatives from governmental bodies and policy making, private and public organizations and institutions, private and public enterprises, and civil movements) and scientific	Moderate number of scientists	Small number of scientists
Interests	Potential users of storylines Potential users of IAAS results Interested in contributing to research activities	Potential users of storylines, e.g. for IAAS Interested in developing storylines at smaller scales or for other (sub-)sectors	
Composition	Broad variety of interests, perspectives, viewpoints, knowledge, non-academic and academic backgrounds, expertise, skills, cultures, and countries	Multiple disciplinary backgrounds Diverse methodological skills and demands (e.g. integrated assessments) Diversity in universities and research institutes Diversity in countries Trained in participatory processes	
Responsibilities	Provide insights from different perspectives on the future of European agriculture and the storylines, e.g. by identifying and prioritizing drivers, checking for consistency of storylines, and reflecting on presentation formats	Advise the process of developing storylines, provide input and feedback at critical stages, provide access to stakeholders	Lead and coordinate development of storylines Draft storylines

3.3. Defining storyline elements

In the third step, storyline elements are identified, clustered and prioritized. Considerable effort should be devoted to this step because the elements define the storyline structure and content and thus the relevance for targeted users (i.e. **salience**). Defining storyline elements is also important for attaining fair treatment of different views, interests, and preferences (i.e. **legitimacy**), maintaining **consistency** across scales, and achieving **richness and creativity.**

Thus, a high level of stakeholder engagement (Level 3) is suggested for this working step, i.e. the core, supporting and stakeholder groups should contribute. Engaging stakeholders and scientists is essential to ensure that selected storyline elements are legitimate, of priority, pertinent and useful for guiding research as well as policy- and decision-making.

We suggest a **three-step procedure** to define storyline elements, starting with the identification of **boundary conditions** given by the global SSPs, followed by **enriching and refining** these boundary conditions to satisfy the goals and purposes of the new storylines, and finalized by **clustering and prioritizing** the storyline elements. Several methods and analytical frameworks can be applied to ensure solid results from this working step. Boundary conditions from the SSPs can be

Table 4
Suggested levels of stakeholder engagement.

Level of stakeholder engagement	Description and preferred format of stakeholder engagement	Degree of interaction
Level 0	The core group manages the respective research phase.	No interaction
Level 1	The core group involves the supporting group in the respective research phase via different communication channels, e.g. through email or telephone.	Mainly information or consultation
Level 2	The core and supporting groups integrate up to ten members from the stakeholder group with different academic, non-academic and professional backgrounds in the respective research phase. The stakeholders are mainly integrated via bilateral communication, e.g. face-to-face discussions or through email and telephone contact, and potentially via workshops or focus group discussions.	Mainly information or consultation
Level 3	The core and supporting groups integrate a large number from the stakeholder group, i.e. more than 10, with different academic, non-academic and professional backgrounds in the respective research phase. Interaction modes are workshops, focus group discussions, qualitative interviews or standardized surveys.	Mainly consultation or collaboration

derived from the relevant literature (e.g. O'Neill et al., 2017; Popp et al., 2017). Enriching and refining storyline elements can also be based on a literature review of regional and sectoral SSPs, recent storyline and scenario exercises related to the spatial scale and sectors of interest, and documents of relevant organizations and institutions, e.g. on future visions for the agricultural sector, the environment and related (sub-) sectors. Including grey literature from relevant organizations and institutions may reduce stakeholder fatigue (Dilling and Berggren, 2015). Furthermore, participatory methods can be applied to directly engage stakeholders. Adequate methods include personal interviews, focus groups and workshops. To structure the results of the previous steps and to cluster and prioritize the storyline elements, analytical frameworks such as the Factors-Actors-Sectors (FAS) Framework (Absar and Preston, 2015; Kok et al., 2006; Rotmans et al., 2000), the Driver-Pressure-State-Impact-Response (DPSIR) Framework (EEA, 1999) or a combination of frameworks (e.g. Ness et al., 2010) can be helpful. Furthermore, recoding and structuring storyline elements in a database can help to compare storyline elements across SSP assumptions and spatial scales, as suggested by Absar and Preston (2015). The database may be updated continuously, e.g. with insights from storyline development processes at national, regional and sub-sectoral levels.

3.4. Drafting storylines

The fourth step is about proposing a structure and developing a draft of the new storylines by combining individual storyline elements and potential directions of change. Thereby, the focus is on **plausibility, richness, creativity, and salience.** Particular attention should be paid to the narrative flow such that clear, understandable and useful storylines are provided that describe potential future developments in an interesting and informative way (Alcamo et al., 2008). We suggest that the core group develops storyline drafts that are discussed with and reviewed by scientists and stakeholders in an iterative process (see working steps five and seven described in sub-sections 3.5 and 3.7).

With respect to the structure, we propose that storylines that aim at enriching global SSPs – such as the Eur-Agri-SSPs – should follow a similar structure and cover the two key parts suggested by the global SSP narratives, i.e. sketch (summary) and additional information (extended storylines; O'Neill et al., 2017). They should be complemented by a third part providing visualizations of storyline elements or storyline-based future outcomes. The first part, the **sketch,** summarizes key storyline elements in a purposefully short manner. It shall be prepared in cooperation with stakeholders, which can positively affect stakeholder buy-in and may help to build a sense of ownership (Garard and Kowarsch, 2017).

The second part on **additional information** shall be structured along the storyline elements identified as most relevant for future development and should discuss drivers, i.e. what could initiate change, why changes could occur and which direction of change could be expected. Examples may be population and urbanization as well as environment and natural resources. The third part aims at **visualizing** the processes underlying the different storylines, dynamics of key storyline elements, and storyline-based future outcomes. Thereby, the differences between and the nuances of the storylines should be made clear. Visualization formats can be developed during the sixth working step (see sub-section 3.6).

3.5. Consistency checks

The fifth working step deals with **consistency checks** of the drafted storylines including the evaluation of vertical and horizontal consistency and the coverage of major stakeholder views (i.e. **legitimacy**). Consistency checks form part of **quality control,** which has been identified as an important component in the storyline development process (Priess and Hauck, 2014). The storyline elements and drafts need to be revised until an acceptable level of consistency is achieved as indicated by the **iterations** in Fig. 1 (thin arrows).

The core and supporting groups shall be involved in this step (Level 1 of stakeholder engagement) in order to ensure that different perspectives and views are considered. Members of the core and supporting groups can be asked to focus on different aspects in the review process, according to their varying knowledge and expertise. For example, experts on environmental management would focus on whether or not storyline elements on demographics, consumption patterns, and environmental policies are consistent, sufficient in detail, and contrasting among the different storylines to frame alternative futures.

Different methods have been suggested for conducting consistency checks. Prominent examples are morphological analysis originally developed by Zwicky (1969) and Zwicky and Wilson (1967) and successfully applied by, e.g., Johansen (2018), Mora (2018), and Ritchey (2011); compatibility matrices and causal loop diagrams related to system dynamics (e.g. Mathijs et al., 2018; Vervoort et al., 2016); and cross impact balance analysis dating back to Weimer-Jehle (2006), with recent applications in climate change research by Ernst et al. (2018), Schweizer and Kriegler (2012), and Schweizer and O'Neill (2014). Another option is to organize an open review process, referring to the procedure for the publication of reports by the Intergovernmental Panel on Climate Change (IPCC). Finally, a combination of methods can increase plausibility of the storylines (Trutnevyte et al., 2014).

3.6. Developing presentation formats

In the sixth step, presentation formats for the storylines are developed. They are targeted at scientific and non-scientific stakeholders and should follow the 'three dimensions of communication', i.e. saliency, robustness and richness (Stephens et al., 2012). Accordingly, visualization of storylines implies to synthesize key dimensions and potential directions of change, to summarize underlying processes, and to illustrate major differences and commonalities. Defining a meaningful title is also part of this working step.

We suggest that the core and the supporting group contribute to developing presentation formats, while members of the stakeholder group may express preferences and could check and evaluate if the presentation reflects their understanding of the storyline. As such, stakeholder engagement may increase **legitimacy** of the storylines (Level 2 of stakeholder engagement).

Presentation formats may include tabular information (e.g. Busch, 2006; McBride et al., 2017), influence chains (e.g. Volkery et al., 2008), causal loop diagrams (e.g. Mathijs et al., 2018), morphological tables (e.g. Mora, 2018), scenario maps (e.g. Priess and Hauck, 2014), mind maps and other visualizations of storyline-based future outcomes (e.g. Palazzo et al., 2017; Saito et al., 2018; Vervoort et al., 2014). Furthermore, the emerging literature on climate services (see e.g. Hewitt et al., 2012) may also stimulate the development of presentation formats.

3.7. Peer and stakeholder review and revision of storylines

Storylines are developed in an **iterative** process where the seventh step of **peer and stakeholder review** plays an important role for increasing **plausibility, consistency, salience, richness and creativity.** The peer and stakeholder review shall focus on the quality criteria for developing storylines, which have been operationalized (see Table 1) to allow for a qualitative or quantitative assessment of goal achievement. The suggestion for operationalizing the defined quality criteria can be transferred into an evaluation sheet to structure and enhance the quality of the peer review process. The results of the review process should be documented and made available to the involved partners and storyline users upon request. Several rounds of reviewing and revising may be necessary (see also Priess and Hauck, 2014), which is indicated by the iterative process in Fig. 1.

The supporting group and members of the stakeholder group should review the drafted storylines in a structured written or oral form (Level 3 of stakeholder engagement). The reviewers can be instructed to focus on different aspects, i.e. quality criteria, in the review process, according to their varying knowledge, interest and experience. However, the core group has to make sure that all quality criteria are sufficiently addressed in the review process. Finally, external experts and laypeople should review the storylines to ensure clarity and readability.

3.8. Dissemination of storylines

In the eighth step, the revised storylines are **disseminated** to inform action and **potential follow-up activities.** Dissemination formats shall be adjusted to the target groups in order to increase the relevance and use of the storylines (i.e. salience). Dissemination activities comprise of scientific and non-scientific formats. They may include scientific articles, conference and workshop presentations, policy briefs, fact sheets and online summaries. An option is to present the newly developed storylines in an online platform where readers and potential users are encouraged to comment and discuss strengths, weaknesses and potential extensions. This feedback could then support follow-up activities and could also stimulate potential (sub-)sectoral extensions.

Ideally, the scientific publications are compiled by the core and the supporting groups, and the non-scientific summaries are produced in cooperation with stakeholders (Level 2 of stakeholder engagement). Co-production of summaries has been proposed as a promising option to improve comprehensibility and general adoption (Garard and Kowarsch, 2017). Referring to the 'climate services' approach (Hewitt et al., 2012), this working step may shift to Level 3 of stakeholder engagement if storylines are mostly targeted at policy and decision makers.

Dissemination can also be seen as a more general procedural step in scientific and non-scientific projects. However, the specificity in the context of disseminating storylines is the complexity of the process and the diversity of actors potentially interested (e.g. with varying cross-sectoral and cross-scale perspectives). Only recently, have cross-sectoral and cross-scale dissemination and communication activities and formats gained in importance.

3.9. Evaluating collaboration for storyline development

The ninth step of **evaluating collaboration** between the core, supporting and stakeholder groups is relevant over the entire period of the storyline development process. Formal evaluation of the storyline development process should help to continuously improve collaboration and thus ownership of the newly developed storylines. The evaluation process shall finally consider if and to what extent the process design requirements are reached (see sub-section 2.3), and what lessons can be drawn from this experience. Suggestions for operationalizing the defined process design requirements are given in Table 2.

Feedback regarding the storyline development process shall be collected informally after crucial working steps or stakeholder contacts in written or oral, e.g. via written or oral form. Topics of interest could be the usefulness of the interaction or event for the respective participant, the clarity of the targets, the adequacy of the format of collaboration and engagement, and the professionalism of facilitators (see e.g. Reed, 2008). At the end of the project, collaborators shall be asked for a more formal feedback, e.g. via a questionnaire or evaluation form. This step may provide valuable insights on how to improve the storyline development process in general, and stakeholder engagement in particular. Similar to dissemination, evaluation is an important step in any research project, in particular if stakeholder engagement plays a role. Therefore, lessons learned from a storyline development process can be useful for projects with a different focus as well.

4. Major challenges of developing new storylines

The protocol provides a reproducible procedure for developing and evaluating new storylines that are consistent with the global SSPs (i.e. Eur-Agri-SSPs). The protocol helps to increase transparency as well as systematic development and evaluation of storylines (Carlsen et al., 2017). Furthermore, it may support the development of Agri-SSPs for other world regions, the development of storylines nested into the Eur-Agri-SSPs, and the development of additional sectoral-SSPs. For example, environmental management concerns that are related to aquatic or systems may require alternative storylines. While the working steps of the protocol can be easily transferred to other sectors, sub-sectors and scales, modifications may be necessary to ensure that the storylines to be developed are relevant and useful to the respective target groups. Challenges remain to meet the defined quality criteria, minimize trade-offs, and design a successful process.

Major challenges emerge from effective stakeholder engagement as well as consistency requirements. Engaging stakeholders throughout the full storyline development process has been suggested to create 'ownership', increase relevance and robustness of storylines, raise the level of precision, widen the spectrum of topics addressed, and help to bring certain futures to fruition (Beck and Mahony, 2017; Kunseler et al., 2015; Reed et al., 2013; Volkery et al., 2008). Difficulties and trade-offs may be encountered in participatory storyline development processes (Alcamo and Henrichs, 2008; McBride et al., 2017). For example, a high level of engagement is typically characterized by actively involving a large number of diverse stakeholders in several phases of the research process, which may be useful for achieving thought-provoking outputs. Such regular interactions are, however, resource demanding and limit the likelihood of stakeholder participation and diversity (McBride et al., 2017; Polk, 2015), in particular in continental-scale storyline development processes. If few assertive stakeholders participate in a multi-phase process, this may distort the focus areas in the discussions and limit the acceptance of the storylines. Furthermore, stakeholder processes typically reveal conflicting interests such as between agricultural production orientation supported by farmers and environmental protection and maintenance pursued by environmentalist organizations. In such situations, researchers have to take a facilitating role in order enhance communicative processes between varying interests (Pohl et al., 2010).

Linking global storylines with regional perspectives is another important challenge (Wardropper et al., 2016), that is to develop a participatory process in a top-down approach. Global boundary conditions given by the SSPs and stakeholder views should both be included in the new storylines, i.e. the Eur-Agri-SSPs. Even though SSPs and Eur-Agri-SSPs differ in scale, scope and detail, the risk of low stakeholder buy-in remains, especially with non-scientific stakeholders. This is mainly because stakeholders are confronted with the SSP logic that they did not contribute to and may disagree with or because they are challenged by high complexities of multi-level interactions of drivers (e.g. Karner et al., 2019). To deal with stakeholder views that diverge from the global SSPs, we suggest bilateral and group discussions on whether some elements in the global SSPs should be outlined in more detail, or if all five global pathways are of relevance for the future of European agriculture and whether one global pathway covers, e.g. two alternative pathways for European agriculture. Potential trade-offs between vertical consistency and salience become evident in this context. To deal with such trade-offs, Alcamo and Henrichs (2008) have suggested to give weights to the quality criteria which are related to the major goals of building and the major purpose of applying storylines. For developing new storylines it is, however, important to remain nested within the global SSPs in order to ensure comparability of results from integrated assessments.

An aspect that needs further attention is the incorporation of established storylines and policy strategies into a new storyline product. Some methodological advances have been made in order to map existing storylines to the global SSPs or consider them in storyline development (Harrison et al., 2019; Kok et al., 2018; Palazzo et al., 2017; Rohat et al., 2018). Timing the storyline development process and adjusting its major goals to the policy process may also help to increase its relevance and usability for stakeholders. A prominent example of concern to policy and decision makers globally is the UN 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs; United Nations, 2015). The SDGs entangle socio-economic and environmental targets. Their interdependence has rarely been described but is crucial for organizing evidence and setting priorities (Nilsson et al., 2016). Plausible, internally consistent descriptions of alternative futures such as the SSPs and the Eur-Agri-SSPs may inform social and environmental management decision and may thus support implementing the SDGs, in particular if the storylines advance the understanding of social environmental systems which help to identify development pathways that enhance socially desirable interactions and reduce trade-offs (Messerli et al., 2019). While Messerli et al. (2019) emphasize the success of interdisciplinary and participatory approaches to bridge the gap between research and policy making, Schneider et al. (2019) ask researchers working on social environmental systems to make their sustainability values explicit in order to increase scientific credibility. The protocol aims to support both, interdisciplinary and participatory research as well as transparency.

Another trade-off is between a high degree of transparency of the storylines and the limited articulation of stakeholders' mental models, cognitive styles and underlying assumptions that drive storyline development (Alcamo and Henrichs, 2008; Boschetti et al., 2016; Priess and Hauck, 2014). In order to overcome these difficulties and trade-offs, effort needs to be devoted to a structured, goal oriented and time-efficient dialogue between scientists and stakeholders and to methodological and contextual transparency, which can – at least partly – be achieved by applying the protocol.

Finally, it is an important though challenging task to encourage out-of-the-box thinking, consider dynamic processes and potential non-linear transformative changes, identify and address uncertainties, and deal with the complexity of interactions and relationships between drivers and their development over time. Drivers and impacts may be hard to distinguish and context-specific (Flick, 2009) even if boundary conditions are derived from the literature and development pathways are based on scientific theory, system understanding and intuitive logics. The iterative storyline development process combined with participatory and creativity methods can help to disentangle interrelations between drivers, pressures and impacts, to explore less likely or even surprising developments, and to make uncertainties and related implications explicit. Bearing in mind the complexity of agricultural systems embedded in broader social environmental systems, the defined scope of the Eur-Agri-SSPs as well as identified drivers and impacts limit completeness of storylines. However, a systematic and structured identification and prioritization of storyline elements establish a basis for agricultural and environmental management.

5. Conclusions

Advancing global SSPs for sectoral applications at European, national and sub-national levels represents a welcome opportunity to increase consistency and comparability of integrated assessments across sectors and scales. IAAS describe, explore and explain how socio-economic and environmental developments affect and are affected by changes in the agricultural sector. Such integrated assessments would benefit from a more systematic and transparent development and evaluation of their underlying storylines. Hence, we have developed an incremental procedure, i.e. a protocol, for developing Shared Socio-economic Pathways for European agriculture – the Eur-Agri-SSPs. Environment and natural resources will be a cluster of storyline elements in the Eur-Agri-SSPs. Thereby, future concerns of environmental management can be considered systematically in IAAS. However, protocol-based storylines of alternative sectors may be required to respond to environmental concerns outside the agricultural domain. The protocol can be used to develop such storylines, and to enrich and refine the SSPs and the Eur-SPPs because it is transferable to other sectors, world regions, and scales. In a next step, the protocol is operationalized and implemented to develop qualitative storylines. The development of nested storylines involves a certain share of subjectivity, which comes at the cost of full replicability. Thus, a comprehensive documentation of the process – as suggested by the protocol – is key in order to ensure that major conclusions are robust and transparent.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

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References

Abildtrup, J., Audsley, E., Fekete-Farkas, M., Giupponi, C., Gylling, M., Rosato, P., Rounsevell, M., 2006. Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach.

Envrion Sci Policy, Assessing Climate Change Effects on Land Use and Ecosystems in Europe 9, 101–115. https://doi.org/10.1016/j.envsci.2005.11.002.
Absar, S.M., Preston, B.L., 2015. Extending the Shared Socioeconomic Pathways for sub-national impacts, adaptation, and vulnerability studies. Glob. Environ. Chang. 33, 83–96. https://doi.org/10.1016/j.gloenvcha.2015.04.004.
Alcamo, J., 2008. The SAS approach: combining qualitative and quantitative knowledge in environmental scenarios. In: Alcamo, J. (Ed.), Developments in Integrated Environmental Assessment, Developments in Integrated Environmental Assessment. Elsevier, pp. 123–150.
Alcamo, J., 2001. Scenarios as Tools for International Environmental Assessments (Environmental Issue Report No. No 24). EEA, European Environment Agency, Copenhagen.
Alcamo, J., Kok, K., Busch, G., Priess, J., 2008. Searching for the future of land: scenarios from the local to global scale. In: Alcamo, J. (Ed.), Environmental Futures: the Practice of Environmental Scenarios Analysis, Developments in Integrated Environmental Assessment. Elsevier, Amsterdam, Oxford, pp. 67–103.
Alcamo, Joseph, Henrichs, T., 2008. Towards guidelines for environmental scenario analysis. In: Alcamo, Jospeh (Ed.), Environmental Futures: the Practice of Environmental Scenario Analysis, Developments in Integrated Environmental Assessment. Elsevier, Amsterdam, Oxford, pp. 13–35.
Beck, S., Mahony, M., 2017. The IPCC and the politics of anticipation. Nat. Clim. Chang. 7, 311–313. https://doi.org/10.1038/nclimate3264.
Bergez, J.-E., Carpy-Goulard, F., Paradis, S., Ridier, A., 2011. Participatory foresight analysis of the cash crop sector at the regional level: case study from southwestern France. Reg. Environ. Chang. 11, 951–961. https://doi.org/10.1007/s10113-011-0232-y.
Bertrand, G., Michalski, A., Rench, L.R., 1999. Scenarios Europe 2010 (Working Paper). European Commission, Forward Studies Unit, Brussels.
Biernacki, P., Waldorf, D., 1981. Snowball sampling: problems and techniques of chain referral sampling. Sociol. Methods Res. 10, 141–163. https://doi.org/10.1177/004912418101000205.
Biewald, A., 2016. Representative agricultural pathways for Europe. In: Presentation at the TradeM International Workshop in Tromsø – Trondheim, Norway.
Biggs, R., Raudsepp-Hearne, C., Atkinson-Palombo, C., Bohensky, E., Boyd, E., Cundill, G., Fox, H., Ingram, S., Kok, K., Spehar, S., Tengö, M., Timmer, D., Zurek, M., 2007. Linking futures across scales: a dialog on multiscale scenarios. Ecol. Soc. 12 https://doi.org/10.5751/ES-02051-120117.
Boschetti, F., Price, J., Walker, I., 2016. Myths of the future and scenario archetypes. Technol. Forecast. Soc. Chang. 111, 76–85. https://doi.org/10.1016/j.techfore.2016.06.009.
Bruno Soares, M., Alexander, M., Dessai, S., 2018. Sectoral use of climate information in Europe: a synoptic overview. Climate Services, Climate services in practice: what we learnt from EUPORIAS 9, 5–20. https://doi.org/10.1016/j.cliser.2017.06.001.
Busch, G., 2006. Future European agricultural landscapes—what can we learn from existing quantitative land use scenario studies? Agriculture, Ecosystems & Environment. Scenario-Based Studies of Future Land Use in Europe 114, 121–140. https://doi.org/10.1016/j.agee.2005.11.007.
Carlsen, H., Klein, R.J.T., Wikman-Svahn, P., 2017. Transparent scenario development. Nat. Clim. Chang. 7, 613. https://doi.org/10.1038/nclimate3379.
Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. 100, 8086–8091. https://doi.org/10.1073/pnas.1231332100.
Cornwall, A., Jewkes, R., 1995. What is participatory research? Soc. Sci. Med. 41, 1667–1676. https://doi.org/10.1016/0277-9536(95)00127-S.
Defila, R., Di Giulio, A., 1999. Evaluating transdisciplinary research. Panorama. Swiss Priority Programme Environment 1, 3–11.
Dilling, L., Berggren, J., 2015. What do stakeholders need to manage for climate change and variability? A document-based analysis from three mountain states in the Western USA. Reg. Environ. Chang. 15, 657–667. https://doi.org/10.1007/s10113-014-0668-y.
Durham, E., Baker, H., Smith, M., Moore, E., Morgan, V., 2014. ThBiodivERsA Stakeholder Engagement Handbook. BiodivERsA, Paris.
EEA, 1999. Environmental Indicators: Typology and Overview (Technical report No. 25). Copenhagen.
Ernst, A., Biß, K.H., Shamon, H., Schumann, D., Heinrichs, H.U., 2018. Benefits and challenges of participatory methods in qualitative energy scenario development. Technol. Forecast. Soc. Chang. 127, 245–257. https://doi.org/10.1016/j.techfore.2017.09.026.
European Commission, 2011. Proposal for a Regulation of the European Parliament and of the Council Establishing Rules for Direct Payments to Farmers under Support Schemes within the Framework of the Common Agricultural Policy, vol. 2011. COM, p. 625 final/2, Brussels, 19.10.2011.
Flick, U., 2009. An Introduction to Qualitative Research, fourth ed. SAGE Publications Ltd, London, California, New Delhi, Singapore.
Frame, B., Lawrence, J., Ausseil, A.-G., Reisinger, A., Daigneault, A., 2018. Adapting global shared socio-economic pathways for national and local scenarios. Climate Risk Management 21, 39–51. https://doi.org/10.1016/j.crm.2018.05.001.
Garard, J., Kowarsch, M., 2017. If at first you don't succeed: evaluating stakeholder engagement in global environmental assessments. Environ. Sci. Policy 77, 235–243. https://doi.org/10.1016/j.envsci.2017.02.007.
Girod, B., Wiek, A., Mieg, H., Hulme, M., 2009. The evolution of the IPCC's emissions scenarios. Environ. Sci. Policy 12, 103–118. https://doi.org/10.1016/j.envsci.2008.12.006.
Gramberger, M., Kok, K., Eraly, E., Stuch, B., 2011. The CLIMSAVE Project. Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe. Report on the first CLIMSAVE European stakeholder workshop.
Gutzler, C., Helming, K., Balla, D., Dannowski, R., Deumlich, D., Glemnitz, M., Knierim, A., Mirschel, W., Nendel, C., Paul, C., Sieber, S., Stachow, U., Starick, A., Wieland, R., Wurbs, A., Zander, P., 2015. Agricultural land use changes – a scenario-based sustainability impact assessment for Brandenburg, Germany. Ecol. Indicat. 48, 505–517. https://doi.org/10.1016/j.ecolind.2014.09.004.
Haigh, T., Koundinya, V., Hart, C., Klink, J., Lemos, M., Mase, A.S., Prokopy, L., Singh, A., Todey, D., Widhalm, M., 2018. Provision of climate services for agriculture: public and private pathways to farm decision-making. Bull. Am. Meteorol. Soc. 99, 1781–1790. https://doi.org/10.1175/BAMS-D-17-0253.1.
Harrison, P., Harmáčková, Z., Aloe Karabulut, A., Brotons, L., Cantele, M., Claudet, J., Dunford, R., Guisan, A., Holman, I., Jacobs, S., Kok, K., Lobanova, A., Morán-Ordóñez, A., Pedde, S., Rixen, C., Santos-Martín, F., Schlaepfer, M., Solidoro, C., Sonrel, A., Hauck, J., 2019. Synthesizing plausible futures for biodiversity and ecosystem services in Europe and Central Asia using scenario archetypes. Ecol. Soc. 24 https://doi.org/10.5751/ES-10818-240227.
Helming, K., Diehl, K., Bach, H., Dilly, O., König, B., Kuhlman, T., Pérez-Soba, M., Sieber, S., Tabbush, P., Tscherning, K., Wascher, D., Wiggering, H., 2011. Ex ante impact assessment of policies affecting land use, Part A: analytical framework. Ecol. Soc. 16, 27. https://doi.org/10.5751/ES-03839-160127.
Henrichs, T., Zurek, M., Eickhout, B., Kok, K., Raudsepp-Hearne, C., Ribeiro, T., van Vuuren, D., Volkery, A., 2010. Scenario development and analysis for forward-looking ecosystem assessments. In: Ash, N., Blanco, H., Brown, C., Garcia, K., Henrichs, T., Lucas, N., Raudsepp-Hearne, C., Simpson, R.D., Scholes, R., Tomich, T. P., Vira, B., Zurek, M. (Eds.), Ecosystems and Human Well-Being. A Manual for Assessment Practitioners. Island Press, Washington, pp. 151–219.
Hewitt, C., Mason, S., Walland, D., 2012. The global framework for climate services. Nat. Clim. Chang. 2, 831–832. https://doi.org/10.1038/nclimate1745.
Hisschemöller, M., Tol, R.S.J., Vellinga, P., 2001. The relevance of participatory approaches in integrated environmental assessment. Integr. Assess. 2, 57–72. https://doi.org/10.1023/A:1011501219195.
Holman, I.P., Brown, C., Janes, V., Sandars, D., 2017. Can we be certain about future land use change in Europe? A multi-scenario, integrated-assessment analysis. Agric. Syst. 151, 126–135. https://doi.org/10.1016/j.agsy.2016.12.001.
Hulme, M., Dessai, S., 2008. Predicting, deciding, learning: can one evaluate the "success" of national climate scenarios? Environ. Res. Lett. 3, 045013 https://doi.org/10.1088/1748-9326/3/4/045013.
Hunt, D.V.L., Lombardi, D.R., Atkinson, S., Barber, A.R.G., Barnes, M., Boyko, C.T., Brown, J., Bryson, J., Butler, D., Caputo, S., Caserio, M., Coles, R., Cooper, R.F.D., Farmani, R., Gaterell, M., Hale, J., Hales, C., Hewitt, C.N., Jankovic, L., Jefferson, I., Leach, J., MacKenzie, A.R., Memon, F.A., Sadler, J.P., Weingaertner, C., Whyatt, J. D., Rogers, C.D.F., Hunt, D.V.L., Lombardi, D.R., Atkinson, S., Barber, A.R.G., Barnes, M., Boyko, C.T., Brown, J., Bryson, J., Butler, D., Caputo, S., Caserio, M., Coles, R., Cooper, R.F.D., Farmani, R., Gaterell, M., Hale, J., Hales, C., Hewitt, C.N., Jankovic, L., Jefferson, I., Leach, J., MacKenzie, A.R., Memon, F.A., Sadler, J.P., Weingaertner, C., Whyatt, J.D., Rogers, C.D.F., 2012. Scenario archetypes: converging rather than diverging themes. Sustainability 4, 740–772. https://doi.org/10.3390/su4040740.
IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Jagosh, J., Macaulay, A.C., Pluye, P., Salsberg, J., Bush, P.L., Henderson, J., Sirett, E., Wong, G., Cargo, M., Herbert, C.P., Seifer, S.D., Green, L.W., Greenhalgh, T., 2012. Uncovering the benefits of participatory research: implications of a realist review for health research and practice. Milbank Q. 90, 311–346. https://doi.org/10.1111/j.1468-0009.2012.00665.x.
Johansen, I., 2018. Scenario modelling with morphological analysis. Technol. Forecast. Soc. Chang. 126, 116–125. https://doi.org/10.1016/j.techfore.2017.05.016.
Karner, K., Cord, A.F., Hagemann, N., Hernandez-Mora, N., Holzkämper, A., Jeangros, B., Lienhoop, N., Nitsch, H., Rivas, D., Schmid, E., Schulp, C.J.E., Strauch, M., van der Zanden, E.H., Volk, M., Willaarts, B., Zarrineh, N., Schönhart, M., 2019. Developing stakeholder-driven scenarios on land sharing and land sparing – insights from five European case studies. J. Environ. Manag. 241, 488–500. https://doi.org/10.1016/j.jenvman.2019.03.050.
Kirchner, M., Schmidt, J., Kindermann, G., Kulmer, V., Mitter, H., Prettenthaler, F., Rüdisser, J., Schauppenlehner, T., Schönhart, M., Strauss, F., Tappeiner, U., Tasser, E., Schmid, E., 2015. Ecosystem services and economic development in Austrian agricultural landscapes — the impact of policy and climate change scenarios on trade-offs and synergies. Ecol. Econ. 109, 161–174. https://doi.org/10.1016/j.ecolecon.2014.11.005.
Kok, K., Patel, M., Rothman, D.S., Quaranta, G., 2006. Multi-scale narratives from an IA perspective: Part II. Participatory local scenario development. Futures 38, 285–311. https://doi.org/10.1016/j.futures.2005.07.006.
Kok, K., Pedde, S., Gramberger, M., Harrison, P.A., Holman, I., 2018. New European socio-economic scenarios for climate change research: operationalising concepts to extend the Shared Socioeconomic Pathways. Regional Environmental Change.
Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. Glob. Environ. Chang. 22, 807–822.
Krütli, P., Stauffacher, M., Flüeler, T., Scholz, R.W., 2010. Functional-dynamic public participation in technological decision-making: site selection processes of nuclear waste repositories. J. Risk Res. 13, 861–875. https://doi.org/10.1080/13669871003703252.

Kunseler, E.-M., Tuinstra, W., Vasileiadou, E., Petersen, A.C., 2015. The reflective futures practitioner: balancing salience, credibility and legitimacy in generating foresight knowledge with stakeholders. Futures 66, 1–12. https://doi.org/10.1016/j.futures.2014.10.006.

Lang, D.J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., Thomas, C.J., 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustain Sci 7, 25–43. https://doi.org/10.1007/s11625-011-0149-x.

Laniak, G.F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., Whelan, G., Geller, G., Quinn, N., Blind, M., Peckham, S., Reaney, S., Gaber, N., Kennedy, R., Hughes, A., 2013. Integrated environmental modeling: a vision and roadmap for the future. Environmental Modelling & Software, Thematic Issue on the Future of Integrated Modeling Science and Technology 39, 3–23. https://doi.org/10.1016/j.envsoft.2012.09.006.

Le Mouël, C., de Lattre-Gasquet, M., Mora, O., 2018. Land Use and Food Security in 2050: a Narrow Road: Agrimonde-Terra. Quae, Versailles Cedex, France.

Mathijs, E., Deckers, J., Kopainsky, B., Nitzko, S., Spiller, A., 2018. Scenarios for EU Farming (Project Report, SUREFarm No. D1.2). KU Leuven.

McBride, M., Lambert, K., Huff, E., Theoharides, K., Field, P., Thompson, J., 2017. Increasing the effectiveness of participatory scenario development through codesign. Ecol. Soc. 22 https://doi.org/10.5751/ES-09386-220316.

Mehdi, B., Lehner, B., Gombault, C., Michaud, A., Beaudin, I., Sottile, M.-F., Blondlot, A., 2015. Simulated impacts of climate change and agricultural land use change on surface water quality with and without adaptation management strategies. Agric. Ecosyst. Environ. 213, 47–60. https://doi.org/10.1016/j.agee.2015.07.019.

Mehdi, B., Lehner, B., Ludwig, R., 2018. Modelling crop land use change derived from influencing factors selected and ranked by farmers in North temperate agricultural regions. Sci. Total Environ. 631–632, 407–420. https://doi.org/10.1016/j.scitotenv.2018.03.014.

Messerli, P., Kim, E.M., Lutz, W., Moatti, J.-P., Richardson, K., Saidam, M., Smith, D., Eloundou-Enyegue, P., Foli, E., Glassman, A., Licona, G.H., Murniningtyas, E., Staniškis, J.K., Ypersele, J.-P. van, Furman, E., 2019. Expansion of sustainability science needed for the SDGs. Nat Sustain 1–3. https://doi.org/10.1038/s41893-019-0394-z.

Michetti, M., Zampieri, M., 2014. Climate–human–land interactions: a review of major modelling approaches. Land 3, 793–833. https://doi.org/10.3390/land3030793.

Mitter, H., Heumesser, C., Schmid, E., 2015. Spatial modeling of robust crop production portfolios to assess agricultural vulnerability and adaptation to climate change. Land Use Policy 46, 75–90. https://doi.org/10.1016/j.landusepol.2015.01.010.

Mitter, H., Kirchner, M., Schmid, E., Schönhart, M., 2014. The participation of agricultural stakeholders in assessing regional vulnerability of cropland to soil water erosion in Austria. Reg. Environ. Chang. 14, 385–400. https://doi.org/10.1007/s10113-013-0506-7.

Mitter, H., Schmid, E., Sinabell, F., 2015. Integrated modelling of protein crop production responses to climate change and agricultural policy scenarios in Austria. Clim. Res. 65, 205–220. https://doi.org/10.3354/cr01335.

Mitter, H., Schönhart, M., Larcher, M., Schmid, E., 2018. The Stimuli-Actions-Effects-Responses (SAER)-framework for exploring perceived relationships between private and public climate change adaptation in agriculture. J. Environ. Manag. 209, 286–300. https://doi.org/10.1016/j.jenvman.2017.12.063.

Mora, O., 2018. Scenarios of land use and food security in 2050. In: Le Mouël, C., de Lattre-Gasquet, M., Mora, O. (Eds.), Land Use and Food Security in 2050: A Narrow Road: Agrimonde-Terra. Quae, Versailles Cedex, France, pp. 206–246.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756. https://doi.org/10.1038/nature08823.

Mylona, K., Maragkoudakis, P., Bock, A.-K., Wollgast, J., Caldeira, S., Ulberth, F., 2016. Delivering on EU Food Safety and Nutrition in 2050 - Future Challenges and Policy Preparedness - EU Science Hub - European Commission (JRC Science for Policy Report No. EUR27957EN). Belgium.

Ness, B., Anderberg, S., Olsson, L., 2010. Structuring problems in sustainability science: the multi-level DPSIR framework. Geoforum 41, 479–488. https://doi.org/10.1016/j.geoforum.2009.12.005.

Nilsson, A.E., Bay-Larsen, I., Carlsen, H., van Oort, B., Bjørkan, M., Jylhä, K., Klyuchnikova, E., Masloboev, V., van der Watt, L.-M., 2017. Towards extended shared socioeconomic pathways: a combined participatory bottom-up and top-down methodology with results from the Barents region. Glob. Environ. Chang. 45, 124–132. https://doi.org/10.1016/j.gloenvcha.2017.06.001.

Nilsson, M., Griggs, D., Visbeck, M., 2016. Policy: map the interactions between sustainable development goals. Nature News 534, 320. https://doi.org/10.1038/534320a.

O'Brien, F.A., 2004. Scenario planning—lessons for practice from teaching and learning. European Journal of Operational Research, Applications of Soft O.R. Methods 152, 709–722. https://doi.org/10.1016/S0377-2217(03)00068-7.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., Vuuren, D.P. van, 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change 122, 387–400. https://doi.org/10.1007/s10584-013-0905-2.

Palazzo, A., Vervoort, J.M., Mason-D'Croz, D., Rutting, L., Havlík, P., Islam, S., Bayala, J., Valin, H., Kadi Kadi, H.A., Thornton, P., Zougmore, R., 2017. Linking regional stakeholder scenarios and shared socioeconomic pathways: quantified West African food and climate futures in a global context. Glob. Environ. Chang. https://doi.org/10.1016/j.gloenvcha.2016.12.002.

Pedde, S., Kok, K., Onigkeit, J., Brown, C., Holman, I., Harrison, P.A., 2018. Bridging uncertainty concepts across narratives and simulations in environmental scenarios. Reg. Environ. Chang. https://doi.org/10.1007/s10113-018-1338-2.

Pohl, C., Rist, S., Zimmermann, A., Fry, P., Gurung, G.S., Schneider, F., Speranza, C.I., Kiteme, B., Boillat, S., Serrano, E., Hadorn, G.H., Wiesmann, U., 2010. Researchers' roles in knowledge co-production: experience from sustainability research in Kenya, Switzerland, Bolivia and Nepal. Sci. Public Policy 37, 267–281. https://doi.org/10.3152/030234210X496628.

Polk, M., 2015. Transdisciplinary co-production: designing and testing a transdisciplinary research framework for societal problem solving. Futures, "Advances in transdisciplinarity 2004-2014" 65, 110–122. https://doi.org/10.1016/j.futures.2014.11.001.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., Vuuren, D.P. van, 2017. Land-use futures in the shared socio-economic pathways. Glob. Environ. Chang. 42, 331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002.

Priess, J., Hauck, J., 2014. Integrative scenario development. Ecol. Soc. 19 https://doi.org/10.5751/ES-06168-190112.

Priess, J.A., Hauck, J., Haines-Young, R., Alkemade, R., Mandryk, M., Veerkamp, C., Gyorgyi, B., Dunford, R., Berry, P., Harrison, P., Dick, J., Keune, H., Kok, M., Kopperoinen, L., Lazarova, T., Maes, J., Pataki, G., Preda, E., Schleyer, C., Görg, C., Vadineanu, A., Zulian, G., 2018. New EU-scale environmental scenarios until 2050 – scenario process and initial scenario applications. Ecosystem Services 29 (Part C), 542–551. https://doi.org/10.1016/j.ecoser.2017.08.006.

Priess, J.A., Schweitzer, C., Wimmer, F., Batkhishig, O., Mimler, M., 2011. The consequences of land-use change and water demands in Central Mongolia. Land Use Policy 28, 4–10. https://doi.org/10.1016/j.landusepol.2010.03.002.

Raymond, C.M., Fazey, I., Reed, M.S., Stringer, L.C., Robinson, G.M., Evely, A.C., 2010. Integrating local and scientific knowledge for environmental management. J. Environ. Manag. 91, 1766–1777. https://doi.org/10.1016/j.jenvman.2010.03.023.

Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. Biol. Conserv. 141, 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014.

Reed, M.S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C.H., Stringer, L.C., 2009. Who's in and why? A typology of stakeholder analysis methods for natural resource management. J. Environ. Manag. 90, 1933–1949. https://doi.org/10.1016/j.jenvman.2009.01.001.

Reed, M.S., Kenter, J., Bonn, A., Broad, K., Burt, T.P., Fazey, I.R., Fraser, E.D.G., Hubacek, K., Nainggolan, D., Quinn, C.H., Stringer, L.C., Ravera, F., 2013. Participatory scenario development for environmental management: a methodological framework illustrated with experience from the UK uplands. J. Environ. Manag. 128, 345–362. https://doi.org/10.1016/j.jenvman.2013.05.016.

Reidsma, P., Bakker, M.M., Kanellopoulos, A., Alam, S.J., Paas, W., Kros, J., de Vries, W., 2015. Sustainable agricultural development in a rural area in The Netherlands? Assessing impacts of climate and socio-economic change at farm and landscape level. Agric. Syst. 141, 160–173. https://doi.org/10.1016/j.agsy.2015.10.009.

Reidsma, P., Wolf, J., Kanellopoulos, A., Schaap, B.F., Mandryk, M., Verhagen, J., Ittersum, M.K. van, 2015. Climate change impact and adaptation research requires integrated assessment and farming systems analysis: a case study in The Netherlands. Environ. Res. Lett. 10, 045004 https://doi.org/10.1088/1748-9326/10/4/045004.

Reimann, L., Merkens, J.-L., Vafeidis, A.T., 2018. Regionalized Shared Socioeconomic Pathways: narratives and spatial population projections for the Mediterranean coastal zone. Reg. Environ. Chang. 18, 235–245. https://doi.org/10.1007/s10113-017-1189-2.

Repko, A.F., Szostak, R., Buchberger, M.P., 2016. Introduction to Interdisciplinary Studies, second ed. SAGE Publications, Inc., California, USA; London, UK; New Delhi, India.

Ritchey, T., 2011. Modeling alternative futures with general morphological analysis. World Futures Review 3, 83–94. https://doi.org/10.1177/194675671100300105.

Rohat, G., Flacke, J., Dao, H., van Maarseveen, M., 2018. Co-use of existing scenario sets to extend and quantify the shared socioeconomic pathways. Clim. Change 151, 619–636. https://doi.org/10.1007/s10584-018-2318-8.

Rose, M., Star, J., 2013. Using Scenarios to Explore Climate Change: A Handbook for Practitioners. National Park Service, U.S. Department of the Interior.

Rosenzweig, C., Jones, J.W., Hatfield, J., Antle, J.M., Ruane, A.C., Boote, K.J., Thorburn, P., Valdivia, R.O., Descheemaeker, K., Porter, C.H., Janssen, S., Bartels, W., Sulivan, A., Mutter, C.Z., 2016. Protocols for AgMIP Regional Integrated Assessments, Version 6.1.

Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P., Antle, J.M., Nelson, G.C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G., Winter, J.M., 2013. The agricultural model intercomparison and improvement project (AgMIP): protocols and pilot studies. Agric. For. Meteorol. 170, 166–182. https://doi.org/10.1016/j.agrformet.2012.09.011.

Rotmans, J., Asselt, M.B.A. van, 2001. Uncertainty management in integrated assessment modeling: towards a pluralistic approach. Environ. Monit. Assess. 69, 101–130. https://doi.org/10.1023/A:1010722120729.

Rotmans, J., van Asselt, M., Anastasi, C., Greeuw, S., Mellors, J., Peters, S., Rothman, D., Rijkens, N., 2000. Visions for a sustainable Europe. Futures 32, 809–831. https://doi.org/10.1016/S0016-3287(00)00033-1.

Rounsevell, M.D.A., Metzger, M.J., 2010. Developing qualitative scenario storylines for environmental change assessment: developing qualitative scenario storylines. Wiley Interdisciplinary Reviews: Clim. Change 1, 606–619. https://doi.org/10.1002/wcc.63.

Ruane, A.C., Rosenzweig, C., Asseng, S., Boote, K.J., Elliott, J., Ewert, F., Jones, J.W., Martre, P., McDermid, S.P., Müller, C., Snyder, A., Thorburn, P.J., 2017. An AgMIP framework for improved agricultural representation in integrated assessment models. Environ. Res. Lett. 12, 125003. https://doi.org/10.1088/1748-9326/aa8da6.

Saito, O., Kamiyama, C., Hashimoto, S., Matsui, T., Shoyama, K., Kabaya, K., Uetake, T., Taki, H., Ishikawa, Y., Matsushita, K., Yamane, F., Hori, J., Ariga, T., Takeuchi, K., 2018. Co-design of national-scale future scenarios in Japan to predict and assess natural capital and ecosystem services. Sustain Sci 1–17. https://doi.org/10.1007/s11625-018-0587-9.

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D.M., Schüngel, J., Priess, J., 2011. An integrated approach to modelling land-use change on continental and global scales. Environ. Model. Softw 26, 1041–1051. https://doi.org/10.1016/j.envsoft.2011.02.013.

Schaldach, R., Meurer, K.H.E., Jungkunst, H.F., Nendel, C., Lakes, T., Gollnow, F., Göpel, J., Boy, J., Guggenberger, G., Strey, R., Strey, S., Berger, T., Gerold, G., Schönenberg, R., Böhner, J., Schindewolf, M., Latynskiy, E., Hampf, A., Parker, P.S., Sentelhas, P.C., 2018. A model-based assessment of the environmental impact of land-use change across scales in Southern Amazonia. Reg. Environ. Chang. 18, 161–173. https://doi.org/10.1007/s10113-017-1244-z.

Schneider, F., Kläy, A., Zimmermann, A.B., Buser, T., Ingalls, M., Messerli, P., 2019. How can science support the 2030 Agenda for Sustainable Development? Four tasks to tackle the normative dimension of sustainability. Sustain Sci. https://doi.org/10.1007/s11625-019-00675-y.

Schönhart, M., Trautvetter, H., Parajka, J., Blaschke, A.P., Hepp, G., Kirchner, M., Mitter, H., Schmid, E., Strenn, B., Zessner, M., 2018. Modelled Impacts of Policies and Climate Change on Land Use and Water Quality in Austria. Land Use Policy.

Schweizer, V.J., Kriegler, E., 2012. Improving environmental change research with systematic techniques for qualitative scenarios. Environ. Res. Lett. 7, 044011 https://doi.org/10.1088/1748-9326/7/4/044011.

Schweizer, V.J., O'Neill, B.C., 2014. Systematic construction of global socioeconomic pathways using internally consistent element combinations. Clim. Change 122, 431–445. https://doi.org/10.1007/s10584-013-0908-z.

Stephens, E.M., Edwards, T.L., Demeritt, D., 2012. Communicating probabilistic information from climate model ensembles—lessons from numerical weather prediction. Wiley Interdisciplinary Reviews: Clim. Change 3, 409–426. https://doi.org/10.1002/wcc.187.

Swart, R.J., Raskin, P., Robinson, J., 2004. The problem of the future: sustainability science and scenario analysis. Glob. Environ. Chang. 14, 137–146. https://doi.org/10.1016/j.gloenvcha.2003.10.002.

Tietje, O., 2005. Identification of a small reliable and efficient set of consistent scenarios. Eur. J. Oper. Res. 162, 418–432. https://doi.org/10.1016/j.ejor.2003.08.054.

Trutnevyte, E., Barton, J., O'Grady, Á., Ogunkunle, D., Pudjianto, D., Robertson, E., 2014. Linking a storyline with multiple models: a cross-scale study of the UK power system transition. Technol. Forecast. Soc. Chang. 89, 26–42. https://doi.org/10.1016/j.techfore.2014.08.018.

United Nations, 2015. Transforming Our World: the 2030 Agenda for Sustainable Development.

Valdivia, R.O., Antle, J.M., Rosenzweig, C., Ruane, A.C., Vervoort, J., Ashfaq, M., Hathie, I., Tui, S.H.-K., Mulwa, R., Nhemachena, C., Ponnusamy, P., Rasnayaka, H., Singh, H., 2015. Representative agricultural pathways and scenarios for regional integrated assessment of climate change impacts, vulnerability, and adaptation. In: Rosenzweig, Cynthia, Hillel, D. (Eds.), Handbook of Climate Change and Agroecosystems. The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments.

van Ittersum, M.K., Ewert, F., Heckelei, T., Wery, J., Alkan Olsson, J., Andersen, E., Bezlepkina, I., Brouwer, F., Donatelli, M., Flichman, G., Olsson, L., Rizzoli, A.E., van der Wal, T., Wien, J.E., Wolf, J., 2008. Integrated assessment of agricultural systems - a component-based framework for the European Union (SEAMLESS). Agric. Syst. 96, 150–165. https://doi.org/10.1016/j.agsy.2007.07.009.

van Vuuren, D.P., Lucas, P.L., Hilderink, H., 2007. Downscaling drivers of global environmental change: enabling use of global SRES scenarios at the national and grid levels. Global Environmental Change, Uncertainty and Climate Change Adaptation and Mitigation 17, 114–130. https://doi.org/10.1016/j.gloenvcha.2006.04.004.

van Vuuren, D.P., Smith, S.J., Riahi, K., 2010. Downscaling socioeconomic and emissions scenarios for global environmental change research: a review. Wiley Interdisciplinary Reviews: Clim. Change 1, 393–404. https://doi.org/10.1002/wcc.50.

Vervoort, J., Helfgott, A., Brzezina, N., Moragues-Faus, A., Lord, S., Avermaete, T., Mathijs, E., 2016. Explorative EU Scenarios.

Vervoort, J.M., Thornton, P.K., Kristjanson, P., Förch, W., Ericksen, P.J., Kok, K., Ingram, J.S.I., Herrero, M., Palazzo, A., Helfgott, A.E.S., Wilkinson, A., Havlík, P., Mason-D'Croz, D., Jost, C., 2014. Challenges to scenario-guided adaptive action on food security under climate change. Glob. Environ. Chang. 28, 383–394. https://doi.org/10.1016/j.gloenvcha.2014.03.001.

Volkery, A., Ribeiro, T., Henrichs, T., Hoogeveen, Y., 2008. Your vision or my model? Lessons from participatory land use scenario development on a european scale. Syst. Pract. Action Res. 21, 459–477. https://doi.org/10.1007/s11213-008-9104-x.

Voros, J., 2003. A generic foresight process framework. Foresight 5, 10–21. https://doi.org/10.1108/14636680310698379.

Wardropper, C., Gillon, S., Mase, A., McKinney, E., Carpenter, S., Rissman, A., 2016. Local perspectives and global archetypes in scenario development. Ecol. Soc. 21 https://doi.org/10.5751/ES-08384-210212.

Weimer-Jehle, W., 2006. Cross-impact balances: a system-theoretical approach to cross-impact analysis. Technol. Forecast. Soc. Chang. 73, 334–361. https://doi.org/10.1016/j.techfore.2005.06.005.

Wiek, A., 2007. Challenges of transdisciplinary research as interactive knowledge generation. Experiences from transdisciplinary case study research. GAIA - Ecological Perspectives for Science and Society 16, 52–57.

Willaarts, B., Magnuszewski, P., Palazzo, A., Parkinson, S., Mayor, B., van Dijk, A.V.M., Langan, S., 2019. Bridging the gap across scales in scenario planning: co-designing water-energy-land visions and pathways in transboundary basins facing global challenges. In: Forum on Scenarios for Climate and Societal Futures. Presented at the Scenarios Forum 2019, Denver, CO.

Wright, G., Bradfield, R., Cairns, G., 2013. Does the intuitive logics method – and its recent enhancements – produce "effective" scenarios? Technological Forecasting and Social Change, Scenario Method: Current developments in theory and practice 80, 631–642. https://doi.org/10.1016/j.techfore.2012.09.003.

Zurek, M.B., Henrichs, T., 2007. Linking scenarios across geographical scales in international environmental assessments. Technol. Forecast. Soc. Chang. 74, 1282–1295. https://doi.org/10.1016/j.techfore.2006.11.005.

Zwicky, F., 1969. Discovery, Invention, Research - through the Morphological Approach. The Macmillan Company, Toronto.

Zwicky, F., Wilson, A.G. (Eds.), 1967. New Methods of Thought and Procedure: Contributions to the Symposium on Methodologies. Springer-Verlag, Berlin Heidelberg.