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Enriching the Shared Socioeconomic Pathways to co-create consistent multi-sector scenarios for the UK

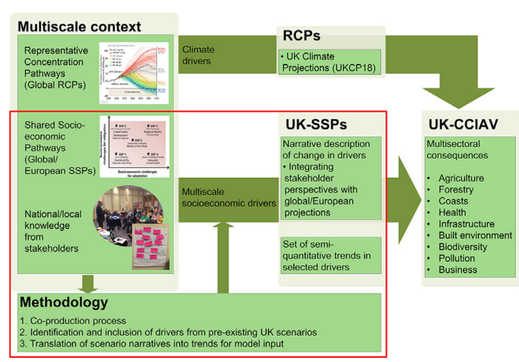
Simona Pedde [a,b,*], Paula A. Harrison [a], Ian P. Holman [c], Gary D. Powney [d,e], Stephen Lofts [a], Reto Schmucki [d], Marc Gramberger [f], James M. Bullock [d]

[a] UK Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster, LA1 4AP, UK
[b] Soil Geography and Landscape Group, Wageningen University, Droevendaalsesteeg 3, 6708 PB Wageningen, the Netherlands
[c] Cranfield Water Science Institute, Cranfield University, College Road, MK43 0AL, Cranfield, UK
[d] UK Centre for Ecology & Hydrology, Benson Lane, Wallingford OX10 8BB, UK
[e] Oxford Martin School & School of Geography and Environment, University of Oxford, Oxford OX1 3BD, UK
[f] Prospex bvba, Vlugestal 6, 3140 Keerbergen, Belgium

HIGHLIGHTS

- Climate change impact and risk assessments need downscaled climate projections and context-relevant socioeconomic scenarios
- We co-created UK versions of the SSPs for use by the UK climate change impacts, adaptation and vulnerability community
- Global and European SSPs were integrated with national knowledge to develop scenarios relevant to the UK context
- The UK-SSPs balance the importance between consistency and legitimacy
- Stakeholder-led national SSPs can be consistent with higher-level SSPs with a well-designed co-production process

GRAPHICAL ABSTRACT



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ABSTRACT

As the pressure to take action against global warming is growing in urgency, scenarios that incorporate multiple social, economic and environmental drivers become increasingly critical to support governments and other stakeholders in planning climate change mitigation or adaptation actions. This has led to the recent explosion of future scenario analyses at multiple scales, further accelerated since the development of the Intergovernmental Panel on Climate Change (IPCC) research community Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). While RCPs have been widely applied to climate models to produce climate scenarios at multiple scales for investigating climate change impacts, adaptation and vulnerabilities (CCIAV), SSPs are only recently being scaled for different geographical and sectoral applications. This is seen in the UK where significant investment has produced the RCP-based UK Climate Projections (UKCP18), but no equivalent UK version of the SSPs exists. We address this need by developing a set of multi-driver qualitative and quantitative UK-SSPs, following a state-of-the-art scenario methodology that integrates national stakeholder knowledge on locally-relevant drivers and indicators with higher level information from European and global SSPs. This was achieved through an intensive participatory process that facilitated the combination of bottom-up and top-down approaches to develop a set of UK-specific SSPs that are locally comprehensive, yet consistent

* Corresponding author at: Soil Geography and Landscape Group, Wageningen University, Droevendaalsesteeg 3, 6708 PB Wageningen, the Netherlands.
E-mail addresses: simona.pedde@wur.nl (S. Pedde), paulaharrison@ceh.ac.uk (P.A. Harrison), i.holman@cranfield.ac.uk (I.P. Holman), gawn@ceh.ac.uk (G.D. Powney), stlo@ceh.ac.uk (S. Lofts), retoschm@ceh.ac.uk (R. Schmucki), marc.gramberger@prospex.com (M. Gramberger), jmbul@ceh.ac.uk (J.M. Bullock).

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with the global and European SSPs. The resulting scenarios balance the importance of consistency and legitimacy, demonstrating that divergence is not necessarily the result of inconsistency, nor comes as a choice to contextualise narratives at the appropriate scale.

1. Introduction

Awareness is growing worldwide that responses to environmental challenges, such as climate change, biodiversity loss and pollution are interdependent, as a result of the interactions between multiple social, economic and environmental drivers (Rosa et al., 2017; IPCC, 2018). To understand the dynamics and effects of these drivers in the medium and long-term, scenarios are typically used by researchers to explore possible futures in the face of uncertainty (Riahi et al., 2017). Scenarios have been defined as: '… *plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships*' (MA, 2005). Exploratory scenarios are useful for understanding 'what might happen in the future' for a region, based on potential trajectories of multiple drivers. These can be translated using impact models into projected consequences for different economic or environmental sectors, such as agriculture, forestry, biodiversity, water, infrastructure and health. This improves understanding of the range of possible outcomes in a region, alerts decision-makers to undesirable future impacts, and enables exploration of the effectiveness of policy options and management strategies (Harrison et al. 2019).

The most recent set of widely applied scenarios for investigating climate change impacts, adaptation and vulnerabilities (CCIAV) implemented by the Intergovernmental Panel on Climate Change (IPCC) research community (Moss et al., 2010) comprise the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011; O'Neill et al., 2015; O'Neill et al., 2017). The SSPs describe a set of alternative plausible trajectories of future societal development, which are based on the best current hypotheses about which societal elements are the most important determinants of challenges to climate change mitigation and adaptation. The SSPs and RCPs were developed in a parallel process and are designed to be scalable (van Ruijven et al., 2014). This allows different socioeconomic assumptions captured in the SSPs to be associated with different emission pathways (RCPs) (Ebi et al., 2014). Crucially, the scalability of the SSPs enables the development of national and multiscale versions of the global SSPs that are consistent both internally and across scales for use by the CCIAV community, facilitating the synthesis of comparable research in future IPCC Assessment Reports. Furthermore, generating national level scenarios from the global SSPs (and, where available, from intermediary continental SSPs) is needed to inform the implementation of national level policies to achieve global targets, such as the Paris Agreement, United Nations Convention on Biological Diversity (CBD) and Sustainable Development Goals (SDGs).

Methodologies to enrich the SSPs for sector-specific applications (e.g. Mitter et al., 2019) and/or with country or local level knowledge (e.g. Kok et al., 2019; Zandersen et al., 2019) have already been developed and applied. Often SSPs are enriched as part of multiscale assessments for several regions and countries (Neumann and Friedland, 2011). This involves nesting outcomes for a region within a country which, in turn, is nested within plausible "worldwide" scenarios (Schweizer and Kurniawan, 2016). For example, Kok et al. (2019) enriched the global SSPs to create European SSPs. Kok and Pedde (2016) then downscaled the European SSPs to the national or regional scale for Hungary, Iberia and Scotland.

A common practice in developing state-of-the-art multiscale scenarios uses model-based downscaling of global scenarios (Neumann and Friedland, 2011). While this practice has the advantage of developing scenarios that are highly consistent over scales and regions (Biggs et al., 2007), it has the disadvantage of excluding local knowledge that is important for identifying locally-relevant drivers and trade-offs. To overcome this disadvantage, recent multiscale SSPs rely on a combination of top-down model-based downscaling using integrated assessment model projections (generally at the global or continental scale) and bottom-up participatory approaches that qualitatively capture local stakeholder insights (Absar and Preston, 2015; Kok et al., 2019; Rosa et al., 2017). Such practices are considered to yield locally relevant scenarios that are consistent with key drivers at the global scale (Nilsson et al., 2017). However, different methods for creating multiscale scenarios have emerged in a relatively ad-hoc manner with little agreement on what constitutes best practice (O'Neill et al., in review). Nevertheless, the methodological assessment of scenarios and models by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Ferrier et al., 2016) identified three key criteria for successful integration of bottom-up and top-down scenario methods to produce credible, reproducible and consistent multiscale scenarios: (i) the development of a participatory process that engages and integrates local/national knowledge; (ii) the identification and inclusion of appropriate locally-relevant drivers and indicators; and (iii) interpretation of the local knowledge from the participatory process on the drivers and indicators of interest into translatable input for impact models.

The UK Government is required under the 2008 Climate Change Act UK to publish a Climate Change Risk Assessment (CCRA) every five years that assesses 'the risks for the United Kingdom from the current and predicted impacts of climate change' (CCRA, 2017). The third CCRA is due to report in 2022 and will rely on research undertaken and published by the UK CCIAV community based on the most recent and relevant scenarios. To this end, the UK Government has invested in the development of a new set of climate scenarios based on the RCPs, the UK Climate Projections 2018 (Met Office, 2019). However, no regionally enriched versions of the global SSPs exist for the UK. This severely restricts analysis of the dynamics of multiple drivers relevant to climate change impacts and the effectiveness of climate change policy and management strategies for mitigating climate change or adapting to its impacts. Therefore, a set of SSPs specifically for the UK is urgently required that will facilitate future national and subnational climate change impact and adaptation applications that are consistent with CCIAV studies at the global and European scales.

This paper addresses this need by developing and implementing a novel approach that integrates bottom-up local knowledge with top-down information from the global and European SSPs to create a consistent set of multi-driver qualitative and quantitative UK-SSPs. Our methodology addresses the three IPBES criteria for producing credible, reproducible and consistent multiscale scenarios and provides an approach that can be applied elsewhere. The set of internally consistent UK-SSPs aims to galvanise UK-specific research on climate change impacts and adaptation that is consistent with the IPCC process, including research and analysis for subsequent Climate Change Risk Assessments. To meet this aim, the methodology has been designed to provide scenarios that cover a broad range of sectors but are not over-specific so as not to constrain potential application and further development spatially or sectorally within the UK.

2. Methodology

2.1. Multiscale scenario design

We developed a consistent framework for regional application of the global SSPs by the UK CCIAV community by integrating bottom-up local and national knowledge with the top-down global and European SSPs. The integration was facilitated by a carefully designed participatory process to generate UK-SSPs. Consistent with the global SSP design and objectives, the UK-SSPs can be combined with RCP-based climate projections for wider application in climate change impact assessments across multiple sectors (Fig. 1) (Harrison et al., 2015; Harrison et al., 2016; Rosa et al., 2017).

How our methodology addresses each of the IPBES recommendations (Ferrier et al., 2016) for developing multiscale scenarios is described in the following sections.

2.2. Co-production process to engage and integrate local/national knowledge

2.2.1. Stakeholder selection

A wide range of stakeholders were selected to provide sufficient breadth and diversity for the UK-SSPs to be both scientifically credible and socially relevant (Lang et al., 2012). Stakeholders were selected to match three categories that ensure representative coverage of a broad range of expertise and viewpoints across the UK CCIAV community, following Lang et al. (2012) and Gramberger et al. (2015). The first category included different discourses to cover both societal (institutional, NGOs, private sector) and scientific (research) expertise. The second category comprised a broad range of CCIAV-relevant sectors as identified in Holman et al. (2014) (see also “UK-CCIAV” box in Fig. 1). The final category included several individual and geographic characteristics to enhance diversity and broader inclusion: age (<30; 30–50; >50 years), gender, geographic location (England, Scotland, Wales, Northern Ireland) and level of professional seniority.

Stakeholders were identified, and a sub-set invited to the stakeholder workshop from a database of more than 200 contacts created by the project team. The full database of contacts was used to gain wider feedback on how to further develop and apply the UK-SSP narratives and trends.

2.2.2. Stakeholder co-production process

An engagement process was designed, which consisted of a 1.5 day facilitated stakeholder workshop followed by a questionnaire. A total of 21 stakeholders participated in the workshop and the follow-up questionnaire, which focused on cross-checking and clarification of the outcomes from the workshop.

The stakeholder workshop alternated plenary and breakout group (five groups) sessions to stimulate lively discussions while guaranteeing coherence of the overall process (Gramberger et al., 2015). Professional facilitation supported this highly interactive process: a lead facilitator was supported by four trained facilitators to guide the process, five “resource people” were available to provide technical guidance to stakeholders on content when needed, and five note-takers were assigned to the breakout groups and plenaries to capture all discussion points. This process enabled the diverse range of stakeholders to bring together their complementary knowledge, viewpoints and insights in an inclusive-environment, while ensuring there was consistency with the global and European SSPs.

The workshop had four main sessions to link the bottom-up and top-down processes:

1. A broad and bottom-up process to identify highly impactful and uncertain socioeconomic drivers, which consisted of an interactive plenary that facilitated the exchange and brainstorming of ideas. This session led to the clustering of these socioeconomic drivers by category and identification of polarities that characterise the UK-relevant dimensions of the driver's uncertainty for each category. The clusters gave structure to the systemic description of interdependencies, specific to the UK context, between these drivers. The

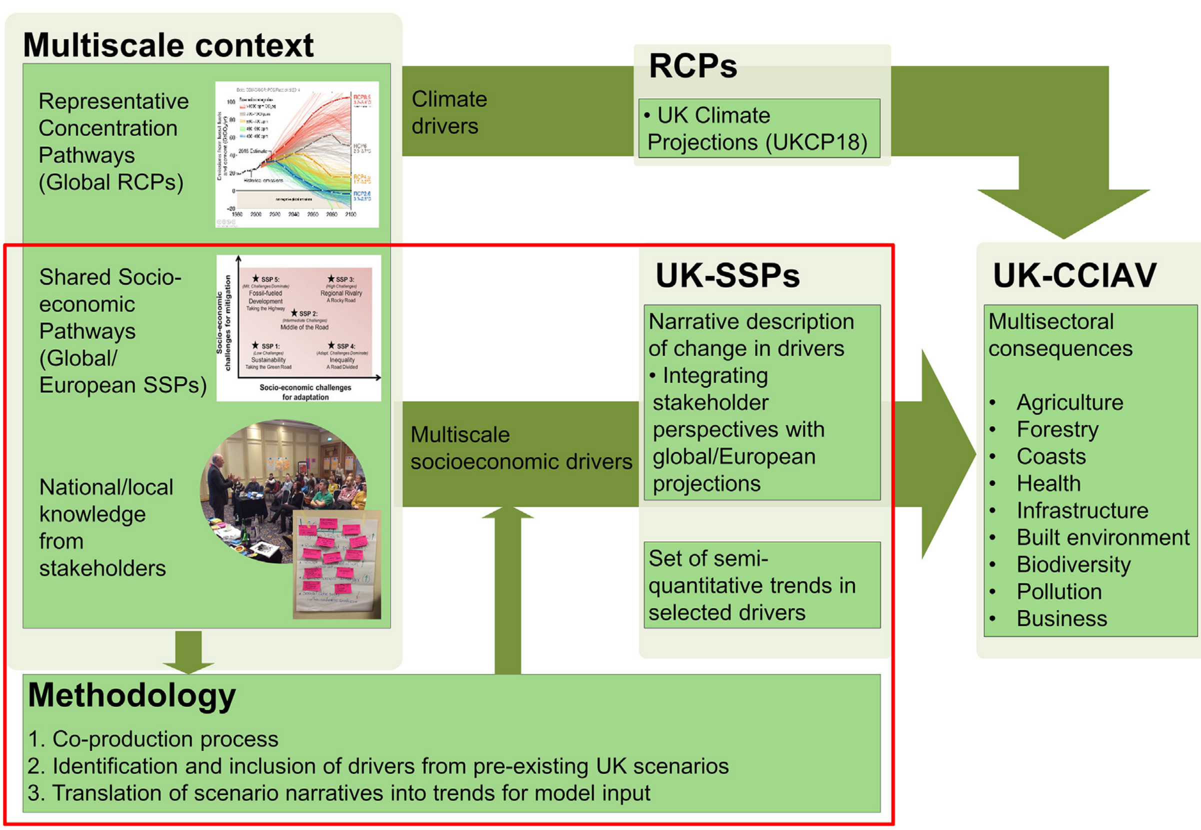

Fig. 1. The multiscale context used to develop the UK-SSPs (in red box) and how they can be combined with climate projections based on the RCPs to assess climate change impacts, adaptation and vulnerabilities (CCIAV) in multiple economic and environmental sectors.

plenary clustering ensured that all discussions were centred around similar systemic issues. At the end of this session, a synthesis of relevant UK-scenario literature was introduced and discussed as described more fully in Section 2.3 and SM-1.

2. The narratives of the global and European SSPs (Fig. 2) were introduced to stakeholders in plenary. In addition, UK trends in Gross Domestic Product and population calculated for each SSP from the global SSP data depository (IIASA, 2013) were presented. These provided a top-down constraint to the following plenary discussions, where stakeholders were asked to map the uncertainty polarities for each UK-specific driver category onto the global/European SSPs.
3. In five breakout groups, one for each UK-SSP, stakeholders were guided through a process aimed at elaborating a narrative for a single UK-SSP that built on the mapping of the UK driver polarities from the previous plenary session. This included the brainstorming of events per UK-SSP and their positioning on a timeline, identifying and elaborating broad lines of development for a range of sectors, and synthesising the main interrelationships between drivers within the scenario. This session combined bottom-up and top-down approaches, ensuring that the UK-SSPs were consistent with the global and European SSPs, while reflecting the specific UK drivers and uncertainties identified in the first two sessions. As part of this process, stakeholders toured around each breakout group so that draft narratives could be shared with the full group of stakeholders to allow questions and discussion. Each group was then able to further refine their individual UK-SSP narrative based on these discussions. This iterative process helped maintain consistency (in terms of level of detail, but not content) between the five UK-SSPs and with the global and European SSPs.
4. Stakeholders discussed trends for eight specific socioeconomic drivers in their individual UK-SSP groups (Section 2.4), each group reaching a consensus on the evolution of the semi-quantitative trends over time (drawn as a graph) and the rationale for these trends. During the facilitated discussions, trade-offs were also highlighted, and the narrative was further refined.

The stakeholders' evaluation of the participatory process was analysed to ensure that the co-production process effectively led to learning and allowed each stakeholder to be involved. The process for all sessions was evaluated very positively (see full results in SM-2).

2.3. Identification and inclusion of appropriate drivers and indicators

To identify the relevant drivers and indicators which form the backbone of the UK-SSPs, pre-existing UK scenarios were evaluated by the project team according to several characteristics, based on the approach of Kok et al. (2015) and Rohat et al. (2018). The scenarios included those of the UK National Ecosystem Assessment (NEA) (Haines-Young et al., 2011), Natural England (Creedy et al., 2009), FORESIGHT Land Use (FLUF, 2010), UKCIP (Hulme et al., 2002), IMPRESSIONS Scottish scenarios (Kok and Pedde, 2016) and the UK Environment Agency's Scenarios 2030 (EA, 2009). The characteristics included the date the scenarios were developed, their relevance to the CCIAV community, their inclusion of multiple sectors, and their inclusion of STEEP (Social, Technological, Economic, Environmental and Political) (Hunt et al., 2012) drivers of change.

Crucially, to avoid constraining stakeholders to pre-existing scenarios, the outcomes of this evaluation exercise were only introduced within the workshop process after stakeholders had brainstormed and

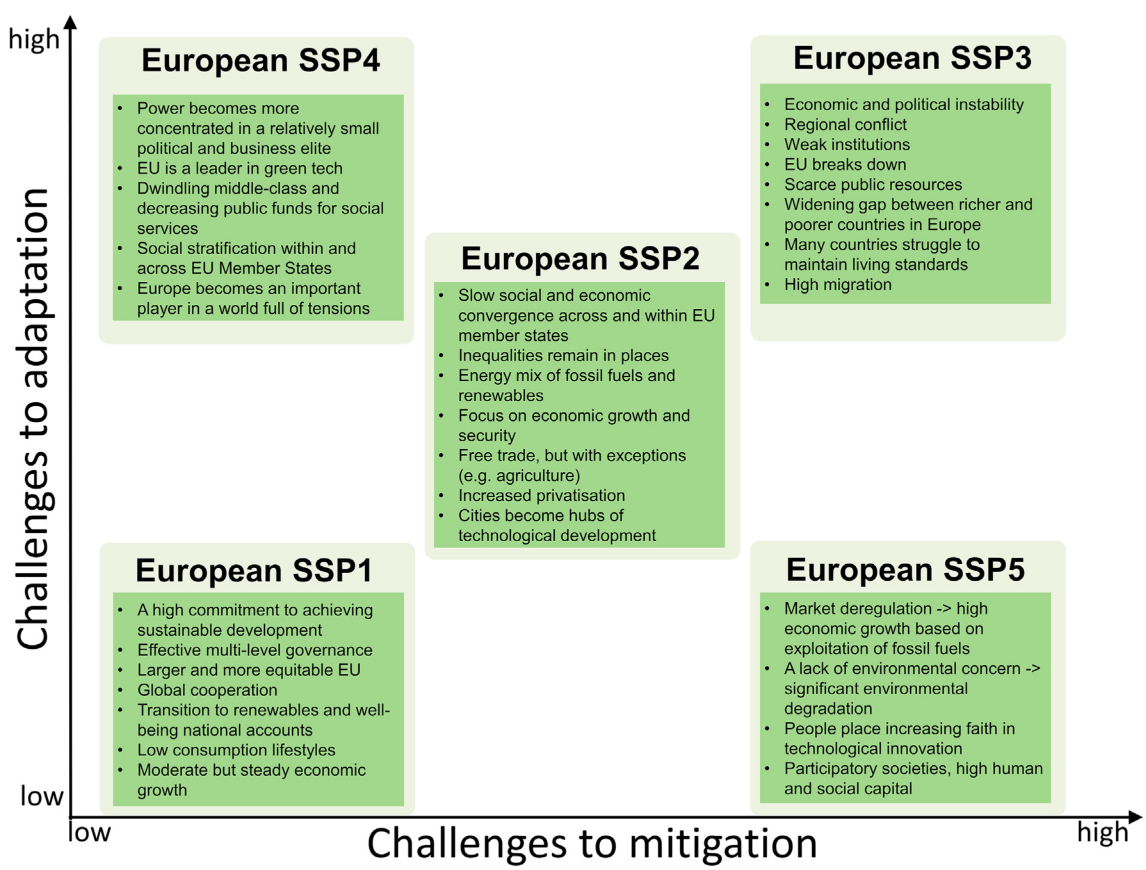

Fig. 2. Overview of European Shared Socioeconomic Pathways (SSPs) elements, directly transferable from the global SSPs and introduced to the UK-SSP workshop during the second session.
(Adapted from Kok et al., 2019.)

clustered UK relevant driving forces of change and their polarities of uncertainty, but before the introduction of the SSPs. The evaluation was then summarised in a plenary presentation to stakeholders to cross-check whether any significant UK drivers were missing from the stakeholders' clusters and to allow stakeholders to consider relevant input for the discussion afterwards (see SM-1 for an overview of the analysis and presentation in the workshop).

2.4. Interpretation of knowledge into translatable model input

The interpretation of information gathered through stakeholder engagement (as described in Section 2.2) is based on the Story and Simulation approach (Alcamo, 2001, 2008). This approach comprises iterating qualitative (participatory) scenarios with quantitative, modelled scenarios to obtain internally consistent and relevant scenarios (Alcamo, 2008). In the case of the UK-SSPs, the qualitative scenarios consist of narratives, tables of driver uncertainties and tables with semi-quantitative trends developed by stakeholders during the facilitated workshop process.

The semi-quantitative trends conceptually link the narratives and CCIAV model input (Pedde et al. 2018). The elaboration of semi-quantitative trendlines enriches the narratives while providing more structure for input to CCIAV assessments. As only a limited amount of time was available within the workshop, we restricted trendline development to eight variables. The first four variables (change in the extent of arable land; change in fertiliser use; change in water abstraction; and change in protected areas for biodiversity) were selected based on two criteria. Firstly, the variables related to the expertise of many of the invited stakeholders and nest well among the key issues for the UK, as mapped in previous scenarios (Section 2.3), while complementing (but not duplicating) the range of generic STEEP drivers and narratives within the European and global SSPs. Secondly, they can inform and constrain the quantification of a wider range of socioeconomic variables by the CCIAV community.

In addition to these four variables, stakeholders also provided trendlines for the five capitals (human, social, manufactured, financial and natural). Capitals are useful indicators of overall wealth in a society, vulnerability of the system, and the ability of society to cope with and adapt to changing circumstances (Porritt, 2007; Dunford et al., 2015; Papadimitriou et al., 2019).

During the semi-quantification exercise stakeholders were asked to categorise the scenario trends for the variables in three-time slices: present to 2040; 2040 to 2070; and 2070 to 2100 compared to current (see example in SM-3). The categories were large, moderate or small decrease, no change, and small, moderate or large increase. Stakeholders were asked to discuss each trend within their UK-SSP group, agree on a consensus answer and draw it on a graph. The stakeholders could provide ancillary information to explain their underpinning thinking.

For each variable, each UK-SSP group was also asked to provide a confidence number ranging from 0 (lowest confidence) to 10 (highest confidence), to capture the confidence that the group had when defining the semi-quantitative trendline of the variable for their scenario. The semi-quantitative trends and their confidence scores are reported in SM-4. The confidence scores were used as part of the assessment of the participatory exercise, as well as to check the internal consistency of the scenarios (from the stakeholder's point of view) (Pedde 2018).

3. Results

We analysed outputs from the stakeholder workshop to develop several UK-SSP products: (i) categories of key UK drivers and their uncertainty polarities mapped to the five UK-SSPs; (ii) narratives describing qualitatively how socioeconomic developments emerge over time in each scenario; and (iii) tables of semi-quantitative trends for a range of drivers to inform impact models. Each of these products is described in this section.

3.1. Mapping UK-specific drivers and their uncertainties to the SSPs

Table 1 synthesises the outputs of sessions 1 and 2 of the workshop. In this Table, the 12 driver categories suggested by the stakeholders cover all the STEEP classes of drivers, with varying emphases relevant to the UK context. In general, the uncertainty polarities associated with these driver categories focus on describing the type or dynamics of transitions, rather than velocity of change. One driver category that included the speed of transition was for green energy, where the uncertainty varied between a gradual transition with relatively slow public uptake to a rapid transition with multiple breakthroughs reinforced by strong societal acceptance.

The environment featured strongly in other driver categories, including land use and environmental policy where the uncertainty polarities were strategic and planned for the benefits of all people vs. free-for-all and unregulated. These uncertainties were thought to be important for determining changes to the agricultural sector and potential knock-on effects for biodiversity. The nature of land and agricultural management practices were also stressed in the driver category on food security and consumption, which combined to influence whether practices were likely to be resource-friendly or over-exploitative and, hence, unsustainable.

Several societal drivers were identified related to demographic change, evolution of societal attitudes, social structures, health and mobility. Stakeholders suggested that the most important aspect of demographic change for the UK was the relative size of the working population. Whether the population had high or low mobility and freedom of movement between urban and rural areas was also considered important. Societal attitudes and behaviour were thought to be a crucial uncertainty in the future, particularly whether individuals felt empowered or disillusioned. Access to health and education services was also recognised, with polarities stated as egalitarian (i.e. access is available to all) or privileged (i.e. access is restricted to a few). The importance of health policies in relation to both human and environmental health were also suggested by stakeholders. A stronger separation between human and environmental health policies was considered to affect the ability to prepare, control and respond to pests and diseases effectively.

Only one driver category concerned technological change and this focused on digital technology and innovation. It included the governance of digital innovation, data transparency and openness, data-driven decision-making and communication, and the development of cyber-physical systems (industry 4.0), with uncertainties focused on whether this will result in net damage or net-benefit to social-ecological-economic systems.

All the driver categories are likely to be influenced by uncertainties about the nature of the economy, particularly how environmental change will be coupled to the future economic system and how this might shape the UK economy in relation to the rest of the world. The uncertainty polarities for this driver focused on whether a change might be fostered by novel non-monetary driven systems or develop within a traditional money-based economy. In addition, the driver category on governance structures was suggested by stakeholders as being key to many other drivers, particularly whether cooperation between the four UK nations will be strong or not, and the level of devolution of decision-making powers. These uncertainties would influence whether policies will be socially divisive or cohesive. In turn, this may affect international relations outside the UK due to changes in geopolitics, trade relations and whether the shift will favour globalisation or nationalism.

The UK-specific driver categories and their uncertainties were mapped by the stakeholders onto the scenario logic of the European/global SSPs to provide the initial framework for the development of the UK-SSPs (see right-hand side of Table 1). In the following, we

Table 1
Summary of UK-specific drivers (bold text) and their uncertainty polarities (shown in purple and green) identified by stakeholders, and their mapping to the European/global SSPs. The left-hand side summarises the outcomes from session 1, providing a short description of each of the final 12 drivers and their uncertainty polarities that were identified by stakeholders as being the most impactful and uncertain for future national development. The right-hand side shows the result of session 2, that is the mapping of these drivers' categories and the relevant uncertainty polarity onto the five SSPs.

UK-relevant uncertainties		SSP1	SSP2	SSP3	SSP4	SSP5
Green energy → transition towards decarbonisation and speed of social uptake						
Gradual transition (purple)	Rapid transition (green)	green	purple	purple	green	purple
Land-use & environmental policy → land management in relation to agricultural intensification, land abandonment, changes to rural policy development and biodiversity protection						
Strategic and planned for benefits of the people (purple)	Free-for-all unregulated (green)	purple	green	green	purple	purple
Food security & consumption → both practices of food production and consumption, such as diets and importance of self-sufficiency and free markets						
Resource-friendly practices (purple)	Resource over-exploitative practices (green)	purple	green	green	green	green
Demographics → drivers that effect the relative size of the working population related to ageing and migration						
Low proportion of working population (purple)	High-proportion of working population (green)	purple	purple	green	green	purple
Evolution of societal attitudes & norms → change in societal values, social cohesion, and behavioural change						
Disillusioned, disengaged & disempowered (purple)	Engaged, empowered & inspired (green)	green	green	purple	purple	purple
Social structure → access to services (health, education, and housing) in % of total population						
Egalitarian (many) (purple)	Privileged (few) (green)	purple	green	green	green	purple
Public & environmental health → diseases affect both human and natural health, advances in medicine and human healthcare and overall risk of epidemics						
Low ability to control and respond (purple)	High ability to control and respond (green)	green	purple	purple	purple	green
Travel & mobility → freedom of movement, travel futures, people and tourism, fuel and transport cost, urban vs rural mobility						
Low (purple)	High (green)	green	green	purple	purple	green
Technology & data → investment in new tech, innovation, digitisation, data-driven decision-making and communication						
Net benefit to social-ecological-economic system (purple)	Net damage to social-ecological-economic system (green)	purple	green	green	green	purple
Nature of the economy → relationship between the environment and the economy, prosperity and economic status in comparison to rest of world						
Non-monetary driven system (purple)	Traditional money-based economy (green)	purple	green	green	green	green
Governmental structure → political cooperation among UK countries, level of devolution of decision-making						
Socially cohesive and effective (purple)	Socially divisive and ineffective (green)	purple	green	green	green	purple
International relations → relationship with trade-partners, international conflicts, terrorism, geopolitical stability						
Nationalist (purple)	Global integration (green)	green	purple	purple	green	green

highlight key aspects of this mapping for each UK-SSP, emphasising differences among the UK-SSPs.

Stakeholders considered that the transition to green energy would be rapid for UK-SSP1 and UK-SSP4 due to fast societal uptake, strategic green energy development policies and interconnected energy markets. In contrast, the uptake would be "very gradual" in UK-SSP3 because of social and economic breakdown, and gradual in UK-SSP2 and UK-SSP5 because of barriers emerging from existing energy infrastructure and old energy production and consumption systems.

Environmental and land-use policies were considered to be strategically planned for the benefit of all people in UK-SSP1 and UK-SSP5, but associated with resource-friendly practices in UK-SSP1 in contrast to over-exploitative practices in UK-SSP5. For UK-SSP4, planning was thought to be strategic, but not for the benefit of all people as this scenario is governed by a strong political and business elite, which results in a combination of technology-driven production together with resource over-exploitive practices in agricultural management. Stakeholders suggested that the lack of strategic land use planning in UK-SSP3, and partly in UK-SSP2, would result in environmental and land use policies being largely unregulated, and lack of radical political will and individual engagement would contribute to the maintenance of over-exploitive practices.

Stakeholders agreed that the welfare state and working conditions, life expectancy and integration of migrant populations would affect the size and nature of the working population under all UK-SSPs. The relative size of the working population was thought to be high in UK-SSP3 and UK-SSP4 because many people would not be able to afford retirement and would have to continue working to support themselves and their families. This would result in people starting work at a younger age, life expectancy decreasing, and increased internal migration (as people move to find work). In the other UK-SSPs with better welfare, people would live longer and hence the population ages, migration would be moderate (with generally high mobility), and well-being (work-life balance) would be emphasised. This was thought to lead to a decrease in the relative proportion of the working population.

Access to public services was considered to be strongly associated with improved social structure and individual well-being. However, an egalitarian social structure would be associated with engaged, empowered and inspired societal actors in UK-SSP1, while in UK-SSP5 passive societal attitudes towards the environment would not favour engagement towards a sustainable society, but rather reliance on technological fixes. In UK-SSP2, access to services would decrease for some, but would be maintained to some extent in the longer term. By contrast, access to services was thought to decrease greatly in UK-SSP3 and UK-SSP4. In these scenarios, social exclusion and privilege is associated with disillusioned, disengaged and disempowered societal attitudes, with a strong link to technological development and individualism in UK-SSP4.

Environmental and public health trends were considered to be driven by technological development and the effectiveness of policies, which relate to societal fabric and individual well-being. As a result, UK-SSP1 was thought to have a high ability to control and respond to pests and diseases, while this was considered to be low for UK-SSP2, UK-SSP3 and UK-SSP4, with UK-SSP5 being more intermediate due to strong technological advances and investments in education and health but a reactive approach to environmental health.

Mobility and travel were considered to be largely affected by societal structures. Stakeholders suggested that socially cohesive decision-making would enable increased mobility, exchange and opportunities in UK-SSP1 and UK-SSP5. This is further reinforced by technological advances and the opportunities these bring. Mobility was thought to increase in UK-SSP4, albeit only for the privileged. In UK-SSP2, while governance would not be as effective, mobility and opportunities would be higher than in UK-SSP3 and for the masses in UK-SSP4. It was agreed that UK-SSP3 would have the lowest mobility of all the UK-SSPs because of highly divisive policy-making and largely ineffective decision-making.

Societal and political transformation was deemed to be affected by the social embedding of how we use technology for the benefit of humans. This was interpreted for UK-SSP1 and UK-SSP2 as having an emphasis on digitalisation, genomics, improving personal care and technological innovation. In UK-SSP3 and UK-SSP4, society does not reap these benefits. While UK-SSP4 is a “technocentric” scenario, loss of jobs due to automation and technological change in an increasingly elitist society was thought to lead to net dis-benefits to society. In UK-SSP3 the lack of governance and resources would limit all technological development, and the little that would occur would be unregulated due to the lack of social and environmental policies. In UK-SSP5 stakeholders decided that technological development would lead to a net benefit for the economic system, but net damage to ecological systems.

In all UK-SSPs except for UK-SSP1, stakeholders decided that the economy would remain a traditional money-based one, meaning that economic growth would be a leading indicator of prosperity and economic status. In contrast, UK-SSP1 was considered to provide opportunities to radically change the current economic system towards a “non-monetary driven system”.

Finally, international relations and trade links were considered to be largely affected by globalisation for UK-SSP4 and UK-SSP5, driven by economic and political interests of key business players. Free-trade relations would dominate in UK-SSP5. In UK-SSP1 globalisation was thought to follow a different path, with a focus on international institutions and policies. By contrast, UK-SSP2 and UK-SSP3 would be less driven by globalisation. In UK-SSP3 stakeholders decided that a focus on nationalism would be driven by strong national security policies in an increasingly fragmenting world, while in UK-SSP2 nationalism would arise from less effective international cooperation.

3.2. Narratives and trends for the UK-SSPs

The further elaboration of the UK system drivers resulted in the development of the full draft narratives of the UK-SSPs (Session 3 of the workshop). The UK-SSP narratives describe how the UK system driver uncertainties in Table 1 lead to cross-sectoral trends in agriculture, forestry, water, biodiversity, urbanisation, health and energy. Sketches of the UK-SSP narratives are presented in Fig. 3, while the full narratives describing time-dependent socioeconomic trends to 2100 are reported in SM-5.

The most detailed and narrowly focused part of the stakeholder process (Session 4 in the workshop) resulted in the semi-quantitative trends for all the UK-SSPs, including their motivation and interlinkages. The results for the selected variables are shown in Table 2 as groups of three arrows representing the three time slices (present to 2040; 2040 to 2070; and 2070 to 2100) in the scenario narratives. In the following, we describe the trends in the four agri-environmental variables quantified by stakeholders in the workshop in the context of the full narratives and trends in related variables from Table 2 and the global SSP data repository (IIASA, 2013).

The IIASA data repository suggests UK population will increase in all UK-SSPs except for UK-SSP3, although the future population size and the timing when population peaks differs between the SSPs. For example, in UK-SSP5 the population is projected to continually increase up to ~128 million by 2100, while in UK-SSP1 population peaks at almost 86 million inhabitants in 2090 then slightly declines. For UK-SSP3 population is projected to peak at 65.5 million in 2040 and then subsequently declines to ~49 million by 2100. In UK-SSP2, population continually increases over time reaching a similar level to UK-SSP1 by 2100 (~85 million). Finally, for UK-SSP4 the population is projected to peak in 2060 at 71 million and then decline to a level similar to today (~63 million).

The GDP trends from the IIASA data repository reflect population trends to some extent. However, GDP is simulated to grow up to 2100 under all UK-SSPs, although at greatly differing rates. The slowest GDP growth is projected in UK-SSP3, especially from the 2080s. UK-SSP4 shows modest growth, followed by higher growth after 2070. UK-SSP1 and UK-SSP2 show similar trends, with more growth than UK-SSP4. UK-SSP5 has the fastest growth with GDP in 2100 of ~21,573 billion US$2005/yr. This is 2.3 times higher than UK-SSP1.

Trends in arable land, fertiliser use and protected areas are closely related to urbanisation and competition for land in the UK-SSPs. This conflict is most marked in UK-SSP4 and UK-SSP5, where increased urbanisation and loss of protected areas follow the same strong trends over time. In UK-SSP4, competition for land is driven by the change from an agricultural subsidy-based system to industrial croplands, which is exacerbated by increasing bioenergy production and urbanisation. Technological development, pushed by the need for more land, allows arable croplands to expand into the uplands. UK-SSP5 also sees the loss of agricultural subsidies, leading to the predominance of market forces. This leads to re-allocation of land to more profitable sectors, such as urbanisation and high-end tourism following re-wilding, which is facilitated by land grabbing in other countries (e.g. in Africa) for agricultural production from 2070.

Competition for land is less apparent in UK-SSP1 due to moderate population growth, behavioural changes that result in less food consumption and less food waste, and a focus on efficient and sustainable agricultural production practices. This counteracts decreases in food imports, resulting in a decrease in total agricultural land, with dietary changes away from meat leading to increases in arable at the expense of intensive pasture. This releases land that can be used for reforestation and restoration of semi-natural habitat, alongside improved nature protection. In UK-SSP2, food imports and sustainable intensification of farming (including genetically-modified crops) result in more

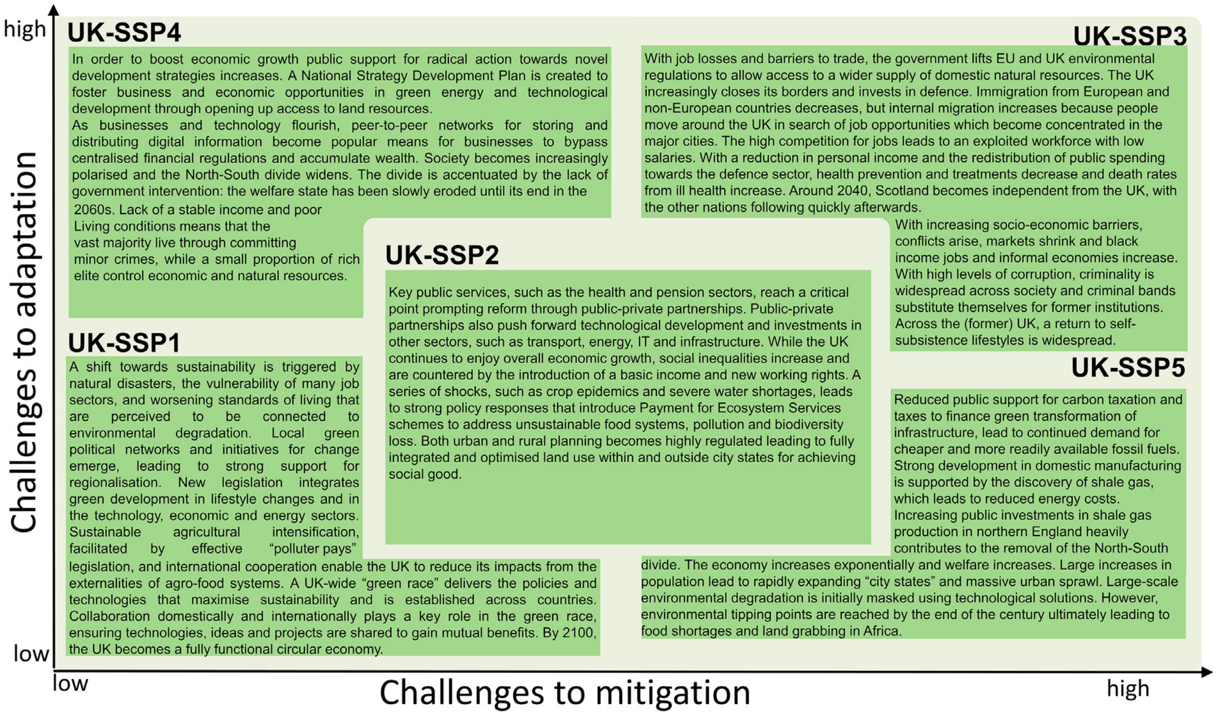

Fig. 3. Summaries of the UK-SSP narratives.

integrated land use, with a focus on livestock farming rather than arable. Even though individual and societal attitudes alter in favour of more protected areas, significant barriers remain, leading to slow changes on the ground. For UK-SSP3 agriculture initially becomes more intensive due to trade barriers limiting food imports, but then a lack of artificial fertilisers leads to an increase in arable land because the land is less productive. Protected areas disappear and in part are lost to arable land. By the 2070s, subsistence farming along with a bartering system leads to increased arable land use.

Trends in water abstraction reflect both behavioural changes (demand-driven) and technology-driven efficiencies in water saving (supply-driven). In UK-SSP1 the overall logic of systemic transformation is translated into declines in water abstraction through the integration of demand and supply-driven management. This first produces a slow change, which accelerates over time with reductions driven by alternatives, such as rainwater harvesting, and more efficient water use and recycling. In UK-SSP2, water abstraction initially increases due to large increases in arable land and population. However, from 2040, water is increasingly recycled and derived through technologies, such as desalination of sea water.

A lack of regulation and early peaks in agricultural and industrial activities in UK-SSP3 lead to increases in water abstraction until the 2030s. This is followed by an overall reduction in water abstraction related to sharp declines in industry and agriculture, a degrading infrastructure and reduced population size. By the 2070s contamination of water means that different ways are needed to harvest water (e.g. rainfall capture), rather than abstraction. In UK-SSP4, developments in water recycling together with the low growth in population and GDP growth, lead to a slight decrease in water abstraction. In UK-SSP5, projected trends for water abstraction were highly divergent (and stakeholders confirmed low confidence in their scoring) depending on whether water abstraction was led by irrigation, energy, or domestic consumption. Particularly challenging was how water demands for irrigation and energy production interrelated with other UK-SSP5 drivers. For example, decreases in arable land result in land use transitions to urbanisation or nature-based tourism, which may require more water abstraction, while the high technological innovation in UK-SSP5 may result in highly water efficient crop varieties or hydroponic systems. The energy mix between gas and oil was also thought to be a key uncertainty by stakeholders that would affect the trend in water abstraction, with an oil-based energy system, which requires water for cooling, leading to greater abstraction.

4. Discussion

4.1. Integration through a participatory process

Using a combination of bottom-up and top-down approaches, we have developed a set of UK-specific Shared Socioeconomic Pathways that are locally comprehensive, yet consistent with the global and European SSPs. While the use of a participatory approach was crucial to represent diverse worldviews (Bohunovsky et al., 2011; Kok and van Vliet, 2011; Chaudhury et al., 2013), its effect on the final narratives can be difficult to reproduce. This relates to the obvious and inevitable limitation of the constrained size and composition of participants in any such exercise, that is, different participants will lead to different narratives. However, it is also affected by the level of "freedom" allowed by the design of the participatory approach to produce narratives of national relevance. Thus, how participatory approaches are designed in each study and integrated with the top-down constraints from the global SSPs has resulted in a proliferation of extended SSP narratives, which vary in their consistency (or inconsistency) across scales and sectors (Mitter et al., 2019), making comparative analyses difficult. While we agree with Mitter et al. (2019) on the need for coordination and shared learning among studies developing SSP extensions, in order to reduce inconsistencies and aid comparability, we demonstrate how the participatory process applied to develop the UK-SSPs has resulted in consistent yet relevant scenarios.

The inclusion of the UK-relevant drivers allowed a strong link between local, regional and global drivers rather than generating divergence. These drivers were identified by the limited number of participants in the stakeholder workshop, but their national relevance

Table 2
Overview of trends in variables for the UK-SSPs. The three arrows represent trends over three time slices: present to 2040; 2040 to 2070; and 2070 to 2100 (each arrow indicates change compared to present, which means that two consecutive arrows of same colour and direction, indicates no change between them). Trends derived from the IIASA data repository, Session 4 of the workshop, and an interpretation of the narratives by the project team (see key).

Variable name	Category	UK-SSP1	UK-SSP2	UK-SSP3	UK-SSP4	UK-SSP5
Population*	Society (Demographics and human development)	↗ ↑ ↑	↗ ↗ ↑	↗ ↘ ↓	↗ ↗ ↗	↗ ↑ ↑
Mobility		↗ ↑ ↑	↗ ↗ ↗	↘ ↓ ↓	↘ ↓ ↓	↗ ↑ ↑
Migration		– ↘ ↘	– – –	↘ ↘ ↘	↘ ↘ ↘	↗ ↗ ↗
Urbanisation		↗ ↗ ↗	↗ ↑ ↑	↗ ↑ ↑	↗ ↑ ↑	↗ ↑ ↑
Social cohesion/ participation		↗ ↑ ↑	↗ ↗ ↗	↘ ↓ ↓	↘ ↓ ↓	↗ ↑ ↑
Tech Development	Technology	↗ ↗ ↑	↗ ↗ ↗	↘ ↓ ↓	↘ ↓ ↓	↗ ↑ ↑
Water abstraction change **		↘ ↓ ↓	↑ ↑ ↗	– ↗ –	↗ ↑ ↑	↗ ↗ ↗
Protected areas **	Environment	↗ ↗ ↑	– – –	↓ ↓ ↓	↓ ↓ ↓	↓ ↓ ↓
Arable land**		↓ ↓ ↓	↑ ↑ ↗	– ↗ –	↗ ↑ ↑	– ↘ ↘
Fertiliser use**		↘ ↓ ↓	↘ ↘ ↘	↑ ↓ ↓	– ↘ ↗	↑ – –
GDP/capita*	Economy and lifestyle	↗ ↗ ↑	↗ ↗ ↑	↗ ↗ ↑	↗ ↗ ↑	↗ ↑ ↑
Inequality		↘ ↓ ↓	↗ – ↘	↗ ↑ ↑	↗ ↑ ↑	↘ ↓ ↓
Overall consumption and diet		↘ ↘ ↓	↗ ↗ ↗	↘ ↓ ↓	↓ ↓ ↓	↗ ↑ ↑
International cooperation	Policies & institutions	↗ ↑ ↑	↗ ↗ ↗	↘ ↓ ↓	↘ ↘ ↘	↗ ↑ ↑
Environmental policy		↗ ↑ ↑	↗ ↗ ↗	↘ ↓ ↓	↘ ↘ ↘	↘ ↓ ↓
Human**	Capitals	↑ ↑ ↑	↗ ↑ ↑	↘ ↓ ↓	– ↗ ↗	↗ ↑ ↑
Social**		↗ ↑ ↑	– – –	↘ ↓ ↓	↘ ↘ ↓	↗ ↑ ↑
Manufactured**		↗ – ↘	↗ ↑ ↑	– ↓ ↓	↗ ↑ ↑	↗ ↑ ↑
Natural**		↗ ↑ ↑	↘ – ↗	↘ ↓ ↓	↘ ↓ ↓	↘ ↓ ↓
Financial**		– ↗ ↗	↗ ↗ ↑	– ↓ ↓	↗ ↑ ↑	↑ ↑ ↑

Legend

↑ High increase compared to present
↗ Modest increase compared to present
– No change compared to present
↘ Modest decrease compared to present
↓ High decrease compared to present
** Trends in the semi-quantitative variables from the workshop
* Trends in the variables modelled from OECD scenarios
[] Trends for all for other variables derived from narratives

was cross-checked against previous UK scenario exercises reported in the literature. They were also compared with drivers used in CCIAV studies, particularly integrated modelling studies that used both socio-economic and climate drivers to simulate their effects on synergies, trade-offs and interdependencies between multiple sectors. For example, Holman et al. (2005), Harrison et al. (2016) and Papadimitriou et al. (2019) identified competition and trade-offs between agricultural land, nature protection, urbanisation and water resources as key uncertainties that are significantly affected by socioeconomic drivers across Europe. Unlike other global scenarios such as the Millennium Ecosystem Assessment scenarios (MA, 2005), nature protection is not included as a main driver in the global SSPs, as highlighted in Rosa et al. (2017). The addition of nature protection in the UK-SSPs strengthens the link not only between local and global SSPs, but also among scenario assessment communities addressing the key global challenges of climate change and biodiversity loss.

Internal consistency, both across trends within the same narrative and between the narratives and their quantification for use in CCIAV models, also strengthens the link across scales. The Story and Simulation (SAS) approach (Alcamo, 2001, 2008; Alcamo and Henrichs, 2008) addresses this consistency through iteration between the narratives, their quantification into model inputs, and the model outcomes in terms of CCIAV impacts. In the UK-SSPs, the semi-quantitative trends were developed directly from the narratives for most drivers, but the narratives were also constrained by the global SSP storylines and the projections from the global SSP data repository (IIASA, 2013) for population and GDP. These future trends for each variable and UK-SSP provide a framing for the direction and relative strength of change in key UK drivers. This ensures that the translation of these trendlines into quantified model inputs by the UK CCIAV research community is consistent across the UK-SSPs and with the global/European SSP context (Pedde 2018). Robustness in internal consistency can also be implied by the confidence scores of participants in the session on developing the semi-quantitative trends (see SM-4; "total confidence": mean = 7, sd = 1.3). This internal consistency was also confirmed with stakeholders after the workshop through a post-workshop questionnaire to iterate and cross-check the narratives (see SM-6).

4.2. Similarities and differences between UK and European/global drivers

The UK-SSPs are embedded within the global and European SSPs (summarised in Fig. 2), but include extensions beyond them to incorporate UK-specific drivers. Hence, it is not surprising that some form of divergence exists, related to the enrichment of the narratives and the addition of trends in a wider range of drivers relevant to the UK context. However, this enrichment does not come at the expense of consistency across the different scales. For example, while GDP trends were not identified by UK stakeholders as a key uncertainty for the UK-SSPs, they still provide a higher scale quantitative indication for other variables on economic performance. This ensures that driving assumptions for both global, European and UK-scale trends remain transparent and comparable.

We explain below how the global, European and UK-SSPs diverge, overlap and complement one another, by comparing STEEP trends at the three scales.

Society - UK-SSP trends in mobility, migration and urbanisation tend to be consistent with their global and European SSP counterparts, except for urbanisation in SSP3. While population decreases in SSP3 at all scales, urbanisation increases as a result of urban sprawl in the European SSP3 (Terama et al., 2019) but, as share of total population, urbanisation is constrained by slow economic growth and limited mobility in UK-SSP3 and global SSP3. Country-specific urbanisation projections for the global SSPs (as share of the total population) show that the UK will have 100% of its population being urbanised by 2100 in SSP1 (Jiang and O'Neill, 2017). This trend is consistent with UK population and GDP trends (derived from the global SSPs), but it does not capture UK-specific spatially-driven trends included in the UK-SSPs, such as mobility between rural and urban populations, legislation for land ownership and regulation for spatial planning. This leads to potential inconsistencies with UK-SSP1 where a fully urbanised population is unlikely due to the narrative focusing on sustainable urban development coupled with activities that maintain an active rural community focused on low input environmentally-friendly agriculture, local food production, and bioenergy production.

Technology – The assumptions on overall trends on technological development are consistent across global, European and UK SSPs. However, the UK-SSPs diverge in relation to their focus on societal embedding of technological development and the effect it has on socioeconomic development. This is particularly visible in UK-SSP4 where overall technological development increases, but which results in net damage to social-ecological-economic systems. This difference has been highlighted in other studies due to the partial mismatch in the scenario logic for SSP4 with existing scenario archetypes (Kok et al., 2019, Pedde et al., 2019a, 2019b) based on its assumption that green technological development underpins low challenges to mitigation, while social inequality underpins high challenges to adaptation.

Environment – Environmental drivers in the UK-SSPs are expressed in terms of their association with land use and environmental policy, as well as trends in food security and consumption. How the polarities for these two driver categories map to the SSPs results in different configurations of land use and trade-offs between sectors. While the trends for land use drivers are similar across scales for all SSPs, cross-sectoral assessments are needed to fully identify potential trade-offs (Harrison et al., 2016). For example, the UK-SSP1 narrative assumes changes in agricultural practices (related to efficiency and sustainable intensification) arising primarily due to increases in domestic food demand, resulting from changing diets and decreased international food imports. However, cross-sectoral modelling of the European SSP1 narrative highlighted major land use trade-offs: agricultural land increases at the expense of forestry due to less intensive agricultural production and decreases in food imports (Harrison et al., 2019). Similar quantitative analysis for the UK (e.g. Holman et al., 2016) may also highlight trade-offs within UK-SSP1, even with the assumption that more efficient and sustainable management enables greater yields per unit of land and hence decreases in agricultural land area.

Economy – The UK-SSP narratives focus on the nature of the economy, overall prosperity and well-being, rather than per capita GDP which is the main economic driver in the global SSPs. In global modelling of the SSPs, GDP growth, population growth, education, physical capital and fossil fuel assets are key driving assumptions for simulating differences in emissions (Dellink et al., 2017). In the UK-SSPs, the future nature of the economy is explained by changes in individual behaviours, government structures, interests of business and international players, land use policy and a focus on well-being.

Policies – Similarly to the global and European SSPs, the UK-SSPs focus on trends in environmental and international policies. The consistency of the UK-SSPs with the global and, especially, European SSPs is achieved through a focus on UK-specific environmental policies and regulations, land ownership and the effect of implementation of subsidies, without referring to specific international or European frameworks. The strong emphasis on land use and agricultural policies in all UK-SSPs are consistent with the European level assumptions on policies, institutions and capacities of actors across scales. From a decision-making perspective, the UK-SSPs emphasise the role of sub-European (UK, national and local) institutions and networks, compared to European SSPs' focus on European institutions and their relations to other actors. This different focus resulted from the stakeholders' perspectives on the relevant levels for decision-making in the UK context, but the different focus is still fully consistent across the UK and European SSPs. The UK-SSPs do not specifically mention the direct effect of European policies, such as the Common Agricultural Policy (CAP) or Water Framework Directive, which are particularly uncertain due to Brexit. They do, however, build on the more generic assumptions on international food imports, commodity trade and international geopolitical stability which characterise the European and global SSPs. The effective or ineffective international and European political and economic cooperation schemes are fully consistent with the European and global SSPs. Further extensions (either local or sector-specific SSPs) should consider specific and sectoral assumptions carefully and could require an adjusted process to balance the need of divergence or consistency across scales or sectors, for example, when developing detailed assumptions on agricultural policy across Europe in the Eur-Agri-SSPs (Mitter et al., 2019) and the UK. Even in finer resolution SSPs, however, the process implemented for the UK-SSPs demonstrates that consideration of the appropriate scale, objectives and relevance for stakeholders does not need to come at the cost of vertical consistency.

4.3. The UK-SSPs compared to other national and regional SSP extensions

The UK-SSPs have been designed to be nested within the global and European SSPs, while taking account of national research and policy needs. Other national SSPs have been developed, including the Japanese SSPs (Chen et al., 2020) and the New Zealand SSPs (Frame et al., 2018). Regional scale SSPs have also been developed for part of the US (Absar and Preston, 2015) and continental scale SSPs for Europe (Reimann et al., 2018; Kok et al., 2019; Zandersen et al., 2019). These studies used a similar nesting approach to allow for both consistency with global SSP narratives (and associated GDP and population projections) and context-specific knowledge. However, the specific demands of the UK decision-making context have required an engagement process that is inclusive and integrative of different worldviews, including non-scientific, policy-relevant knowledge. Similar to Palazzo et al. (2017) and Nilsson et al. (2017), the inclusion of such different worldviews can lead to more nuanced divergence from the global assumptions.

The UK-SSPs start from the national policy agenda and stakeholder-led uncertainties which are subsequently mapped onto the global and European SSP assumptions, in contrast to higher level downscaled versions of the SSPs which start from the global SSPs and disaggregate each narrative assumption using a one-to-one nesting approach. Our combination of top-down and bottom-up approaches, while still echoing the distinction between “consistent” and “coherent” scenarios across scales from Zurek and Henrichs (2007), could indicate the emergence of a novel policy-driven paradigm in multiscale scenario development. This effectively responds to the need for scientific credibility in the form of consistency and comparability criteria on the one hand, and legitimacy and policy relevance on the other hand (Frame et al., 2018). By balancing the importance of consistency and legitimacy, the UK-SSPs demonstrate that divergence is not necessarily the result of inconsistency, nor comes as a choice. Stakeholder-led downscaled and nested scenarios can be as consistent with higher level scenarios provided that there is appropriate facilitation. The facilitated process can thus be designed to “extend”, i.e. enrich higher level narratives with complementary details that increase relevance for stakeholders and enable higher resolution quantitative model assessment. This will be further tested in future research by further extending the UK-SSPs for the four countries of the UK and developing spatially-explicit quantifications of key drivers from the semi-quantitative trends for use by impact modellers.

5. Conclusions

Understanding future socioeconomic dynamics is increasingly acknowledged by many governments, including the UK, to be crucial, along with climate scenarios, for the development of effective climate change mitigation and adaptation policy and management strategies. We address this need by developing a set of multi-driver qualitative and quantitative UK-SSPs through a professionally facilitated participatory process that integrates bottom-up local/national knowledge and locally-relevant drivers with top-down information from the global and European SSPs. By seeking to balance scientific credibility, legitimacy and policy relevance, the final set of internally consistent UK-SSPs aim to galvanise UK-specific research on climate change impacts and adaptation. The UK-SSPs complement the RCP-based UK Climate Projections, which together provide the basis for a multitude of CCIAV applications, such as projecting impacts and risks on human health, water resources, agriculture, biodiversity, infrastructure and the built environment, and assessing opportunities and trade-offs related to adaptation and mitigation actions by different actors. Such research is vital for informing subsequent UK Climate Change Risk Assessments using an evidence base that is consistent with international studies and future IPCC Assessment Reports.

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CRediT authorship contribution statement

Simona Pedde: Conceptualization, Methodology, Investigation, Original draft preparation, Review & editing, Visualisation. **Paula A. Harrison:** Conceptualization, Methodology, Investigation, Original draft preparation, Review & editing, Commentary, Management and Co-ordination. **Ian P. Holman:** Critical review, Investigation, Commentary, Review & editing. **Gary D. Powney:** Investigation, Commentary, Review & editing. **Stephen Lofts:** Investigation, Commentary, Review & editing. **Reto Schmucki:** Investigation, Commentary, Review & editing. **Marc Gramberger:** Investigation, Commentary, Review & editing. **James M. Bullock:** Conceptualization, Methodology, Investigation, Critical Review, Management and coordination.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

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.

Alcamo, J., 2001. Scenarios as Tools for International Environmental Assessments. Copenhagen.

Alcamo, J., 2008. The SAS approach: combining qualitative and quantitative knowledge in environmental scenarios. Environmental Futures: The Practice of Environmental Scenario Analysis. vol. 2, pp. 123–150.

Alcamo, J., Henrichs, T., 2008. Towards guidelines for environmental scenario analysis. Environmental Futures: The Practice of Environmental Scenario Analysis, pp. 13–35.

Biggs, R., Raudsepp-Hearne, C., Atkinson-Palombo, C., Bohensky, E., Boyd, E., Cundill, G., Fox, H., Ingram, S., Kok, K., Spehar, S., 2007. Linking futures across scales: a dialog on multiscale scenarios. Ecol. Soc. 12, 17.

Bohunovsky, L., Jäger, J., Omann, I., 2011. Participatory scenario development for integrated sustainability assessment. Reg. Environ. Chang. 11, 271–284.

CCRA, 2017. Climate Change Risk Assessment 2017.

Chaudhury, M., Vervoort, J., Kristjanson, P., Ericksen, P., Ainslie, A., 2013. Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. Reg. Environ. Chang. 13, 389–398.

Chen, H., Matsuhashi, K., Takahashi, K., Fujimori, S., Honjo, K., Gomi, K., 2020. Adapting global shared socio-economic pathways for national scenarios in Japan. Sustain. Sci.

Creedy, J.B., Doran, H., Duffield, S.J., George, N.J., Kass, G.S., 2009. England's natural environment in 2060 - issues, implications and scenarios. Natural England Research Reports Number 031.

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. Glob. Environ. Chang. 42, 200–214.

Dunford, R., Harrison, P.A., Jäger, J., Rounsevell, M.D.A., Tinch, R., 2015. Exploring climate change vulnerability across sectors and scenarios using indicators of impacts and coping capacity. Clim. Chang. 128, 339–354.

EA, 2009. Environment Agency Scenarios 2030. Environment Agency, Bristol, UK.

Ebi, K., Hallegatte, S., Kram, T., Arnell, N., Carter, T., Edmonds, J., Kriegler, E., Mathur, R., O'Neill, B., Riahi, K., Winkler, H., Van Vuuren, D., Zwickel, T., 2014. A new scenario framework for climate change research: background, process, and future directions. Clim. Chang. 122, 363–372.

Ferrier, S., Ninan, K., Leadley, P., Alkemade, R., Acosta, L., Akçakaya, H., Brotons, L., Cheung, W., Christensen, V., Harhash, K., 2016. The Methodological Assessment Report on Scenarios and Models of Biodiversity and Ecosystem Services. Secretariat of the Intergovernmental Platform for Biodiversity and Ecosystem Services, Bonn, Germany.

FLUF, 2010. Foresight Land Use Futures Project. Final Project Report, London, UK.

Frame, B., Lawrence, J., Ausseil, A.-G., Reisinger, A., Daigneault, A., 2018. Adapting global shared socio-economic pathways for national and local scenarios. Clim. Risk Manag. 21, 39–51.

Gramberger, M., Zellmer, K., Kok, K., Metzger, M., 2015. Stakeholder integrated research (STIR): a new approach tested in climate change adaptation research. Clim. Chang. 128, 201–214.

Haines-Young, R., Paterson, J., Potschin, M., Wilson, A., Kass, G., 2011. The UK NEA Scenarios: Development of Storylines and Analysis of Outcomes.

Harrison, P.A., Holman, I.P., Berry, P.M., 2015. Assessing cross-sectoral climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project. Clim. Chang. 128, 153–167.

Harrison, P.A., Dunford, R.W., Holman, I.P., Rounsevell, M.D.A., 2016. Climate change impact modelling needs to include cross-sectoral interactions. Nat. Clim. Chang. 6, 885–890.

Harrison, P.A., Dunford, R.W., Holman, I.P., Cojocaru, G., Madsen, M.S., Chen, P.-Y., Pedde, S., Sandars, D., 2019. Differences between low-end and high-end climate change impacts in Europe across multiple sectors. Reg. Environ. Chang. 19, 695–709. https://doi.org/10.1007/s10113-018-1352-4.

Holman, I.P., Harrison, P.A., Metzger, M.J., 2016. Cross-sectoral impacts of climate and socio-economic change in Scotland: implications for adaptation policy. Reg. Environ. Chang. 16, 97–109.

Hulme, M., Turnpenny, J., Jenkins, G., 2002. Climate Change Scenarios for the United Kingdom: The ukcip02 Briefing Report.

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.

IIASA, 2013. SSP Database (Version 0.93).

IPCC, 2018. IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty (In press).

Jiang, L., O'Neill, B.C., 2017. Global urbanization projections for the Shared Socioeconomic Pathways. Glob. Environ. Chang. 42, 193–199.

Kok, K., Pedde, S., 2016. IMPRESSIONS Socio-economic Scenarios. IMPRESSIONS project Available from. http://www.impressions-project.eu/documents/1/.

Kok, K., van Vliet, M., 2011. Using a participatory scenario development toolbox: added values and impact on quality of scenarios. Journal of Water and Climate Change 2, 87–105.

Kok, K.C., Hesselbjerg, J., Sloth Madsen, M., Pedde, S., Gramberger, M., Jäger, J., Carter, T., 2015. Evaluation of Existing Climate and Socio-economic Scenarios Including a Detailed Description of the Final Selection.

Kok, K., Pedde, S., Gramberger, M., Harrison, P.A., Holman, I.P., 2019. New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. Reg. Environ. Chang. 19, 643–654. https://doi.org/10.1007/s10113-018-1400-0.

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.

MA, M.E.A., 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Met Office UKCP18 Science Overview Report, 2019. In: Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fosser, G., Fung, F., Gohar, L., Good, P., Gregory, J., Harris, G., Howard, T., Kaye, N., Kendon, E., Krijnen, J., Maisey, P., McDonald, R., McInnes, R., McSweeney, C., Mitchell, J.F.B., Murphy, J., Palmer, M., Roberts, C., Rostron, J., Sexton, D., Thornton, H., Tinker, J., Tucker, S., Yamazaki, K., Belcher, S. (Eds.), Met Office Hadley Centre, Exeter updated March. Authors. (73pp).

Mitter, H., Techen, A.-K., Sinabell, F., Helming, K., Kok, K., Priess, J.A., Schmid, E., Bodirsky, B.L., Holman, I., Lehtonen, H., Leip, A., Le Mouël, C., Mathijs, E., Mehdi, B., Michetti, M., Mittenzwei, K., Mora, O., Øygarden, L., Reidsma, P., Schaldach, R., Schönhart, M., 2019. A protocol to develop Shared Socio-economic Pathways for European agriculture. J. Environ. Manag. 109701, 252.

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. vol. 463 pp. 747–756.

Neumann, T., Friedland, R., 2011. Climate Change Impacts on the Baltic Sea. Pages 23–32 Global Change and Baltic Coastal Zones. Springer.

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.

O'Neill, B., Kriegler, E., Riahi, K., Ebi, K., Hallegatte, S., Carter, T., Mathur, R., van Vuuren, D., 2015. A new scenario framework for climate change research: the concept of Shared Socioeconomic Pathways. Clim. Chang. 122, 387–400.

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.

O'Neill, B.C., Carter, T., Ebi, K.L., Harrison, P.A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B., Riahi, K., Sillmann, J., van Ruijven, B., van Vuuren, D., Carlisle, D., Conde, C., Fuglestvedt, J., Green, C., Hasegawa, Tomoko, Leininger, J., Monteith, S., Pichs-Madruga, R., 2020. Achievements and needs for the climate change scenario framework. Nat. Clim. Chang. (in review).

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. 45, 227–242.

Papadimitriou, L., Holman, I.P., Dunford, R., Harrison, P.A., 2019. Trade-offs are unavoidable in multi-objective adaptation even in a post-Paris Agreement world. Sci. Total Environ. 696, 134027.

Pedde, S., Kok, K., Hölscher, K., Oberlack, C., Harrison, P.A., Leemans, R., 2019a. Archetyping shared socioeconomic pathways across scales: an application to Central Asia and European case studies. Ecol. Soc. 24, 30. https://doi.org/10.5751/ES-11241-240430.

Pedde, S.K., Kasper, Onigkeit, Janina, Brown, Calum, Holman, Ian, Harrison, Paula, 2019b. Bridging uncertainty concepts across narratives and simulations in environmental scenarios. Reg. Environ. Chang. 19, 655–666. https://doi.org/10.1007/s10113-018-1338-2.

Porritt, J., 2007. The five capitals framework. Capitalism as if the World Matters. Earthscan, London, UK, pp. 137–142.

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.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42, 153–168.

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. Chang. 151, 619–636.

Rosa, I.M.D., Pereira, H.M., Ferrier, S., Alkemade, R., Acosta, L.A., Akcakaya, H.R., den Belder, E., Fazel, A.M., Fujimori, S., Harfoot, M., Harhash, K.A., Harrison, P.A., Hauck, J., Hendriks, R.J.J., Hernández, G., Jetz, W., Karlsson-Vinkhuyzen, S.I., Kim, H., King, N., Kok, M.T.J., Kolomytsev, G.O., Lazarova, T., Leadley, P., Lundquist, C.J., García Márquez, J., Meyer, C., Navarro, L.M., Nesshöver, C., Ngo, H.T., Ninan, K.N., Palomo, M.G., Pereira, L.M., Peterson, G.D., Pichs, R., Popp, A., Purvis, A., Ravera, F., Rondinini, C., Sathyapalan, J., Schipper, A.M., Seppelt, R., Settele, J., Sitas, N., van Vuuren, D., 2017. Multiscale scenarios for nature futures. Nature Ecology & Evolution 1, 1416–1419.

Schweizer, V.J., Kurniawan, J.H., 2016. Systematically linking qualitative elements of scenarios across levels, scales, and sectors. Environ. Model. Softw. 79, 322–333.

Terama, E., Clarke, E., Rounsevell, M.D.A., Fronzek, S., Carter, T.R., 2019. Modelling population structure in the context of urban land use change in Europe. Reg. Environ. Chang. 19, 667–677. https://doi.org/10.1007/s10113-017-1194-5.

van Ruijven, B., Levy, M., Agrawal, A., Biermann, F., Birkmann, J., Carter, T., Ebi, K., Garschagen, M., Jones, B., Jones, R., Kemp-Benedict, E., Kok, M., Kok, K., Lemos, M., Lucas, P., Orlove, B., Pachauri, S., Parris, T., Patwardhan, A., Petersen, A., Preston, B., Ribot, J., Rothman, D., Schweizer, V., 2014. Enhancing the relevance of Shared Socioeconomic Pathways for climate change impacts, adaptation and vulnerability research. Clim. Chang. 122, 481–494.

van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., Rose, S., 2011. The representative concentration pathways: an overview. Clim. Chang. 109, 5–31.

Zandersen, M., Hyytiäinen, K., Meier, H.E.M., Tomczak, M.T., Bauer, B., Haapasaari, P.E., Olesen, J.E., Gustafsson, B.G., Refsgaard, J.C., Fridell, E., Pihlainen, S., Le Tissier, M.D.A., Kosenius, A.-K., Van Vuuren, D.P., 2019. Shared socio-economic pathways extended for the Baltic Sea: exploring long-term environmental problems. Reg. Environ. Chang. 19, 1073–1086.

Zurek, M.B., Henrichs, T., 2007. Linking scenarios across geographical scales in international environmental assessments. Technol. Forecast. Soc. Chang. 74, 1282–1295.