Advancing the development and use of climate-change scenarios

A multi-scale analysis to explore socio-economic European futures

Simona Pedde

Thesis committee

Promotor
Prof. Dr Rik Leemans
Professor of Environmental Systems Analysis
Wageningen University & Research

Co-promotor
Dr Kasper Kok
Assistant Professor, Soil Geography and Landscape Group
Wageningen University & Research

Other members
Prof. Dr Katrien Termeer, Wageningen University & Research
Dr Bas van Ruijven, IIASA, Laxenburg, Austria
Prof. Dr Detlef van Vuuren, PBL, Utrecht University
Dr Monika Zurek, Oxford University, UK

This research was conducted under the auspices of the C.T. de Wit Graduate School of Production Ecology & Resource Conservation (PE&RC)

Advancing the development and use of climate-change scenarios
A multi-scale analysis to explore socio-economic European futures

Simona Pedde

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 29 January 2019
at 4 p.m. in the Aula.

Simona Pedde
Advancing the development and use of climate-change scenarios
A multi-scale analysis to explore socio-economic European futures,
146 pages.

PhD thesis, Wageningen University, Wageningen, The Netherlands (2019)
With references, with summary in English

ISBN 978-94-6343-559-8
DOI: 10.18174/466803

Acknowledgements

The best part is written last. It is my pleasure to acknowledge the positive influence that so many colleagues and friends had on my work, experience, personal growth and life.

I would like to express my gratitude to my ‘official’ supervision-team, that is my promotor and supervisor. Thanks to my promotor, Prof. Dr Rik Leemans, for his responsibility, commitment and availability. Thanks also for detailed comments on hyphenation rules and much, much more! Rik, your guidance helped me throughout the thesis, until the very end! Thanks to my supervisor, Dr Kasper Kok. To those around me, it is common knowledge that I had a wonderful PhD experience, and I owe this largely to Kasper. Kasper, you respected me as your peer, granting all freedom I needed, yet advising and sharing your knowledge and network. You always supported me. I could not imagine a better supervision-team.

Kasper, first thing after our first brainstorm, you ‘threw me’ in the midst of an IMPRESSIONS project modellers meeting, in September 2014, in Pisa. I didn‘t know anyone then, except for some names in my EndNote library. But since then, all IMPRESSIONISTs have become a real part of my research and, some, of my life. Thanks to all of IMPRESSIONS for the lively discussions, research input and questions, novel methodologies, life-changing lessons, crazy nights out, even-crazier travels and runs etc. As I don‘t have space for all unfortunately, I’ll just mention some of you, knowing that my thanks are sincerely directed to all.

I’d like to mention those who I consider my ‘unofficial advisory-team’. And, incidentally, you are all British! I would like to thank Dr Jill Jäger, Prof. Dr Ian Holman, Dr Calum Brown and our coordinator, Prof. Dr Paula Harrison. You all are exceptionally knowledgeable scientists as demonstrated by your research output, but not only. In this ‘sorry-I‘m-extremely-busy’ world, you still found time to send valuable feedback, share life experiences and discuss with me many of the concepts that I would bring forward and finalise in this thesis. It is an honour to consider you my co-supervisors. Paula, thanks for ignoring Brexit and inviting me to pursue the UK-SSPs adventure in Lancaster! I’m humbled by the opportunity to working at CEH as part of the UK-SCAPE team guided by Prof. Dr James Bullock.

Going back to IMPRESSIONS, the British team would not be complete without the Scottish-case-study team guided by Dr Liz Clarke, Dr Miriam Dunn and Prof. Mark Rounsevell. Thanks to all for contributing to my papers and sharing your wine knowledge. My heartfelt thanks also to the other ‘Brits’: Ms Alison Smith and Dr Robert Dunford for their sharp contribution to scientific discussions and papers. Thanks also to Dr Aidan Keith for lively discussions during IMPRESSIONS and at CEH.

Thanks to the international case-study teams for unforgettable workshops, discussions and work together throughout Spain, Portugal, Hungary, Kazakhstan and Azerbaijan. I'd like to thank in particular Dr David Tabara and the fantastic artistic team, Dr Tiago Capela and Dr Maria João, Dr Henrik Carlsen, Dr Magnus Benzie, Mr Adis Dzebo, Dr Laszlo Pinter and Mrs Linda Horvath. Thanks to all stakeholders as well. You contributed with your insights, expertise and critical questions. With some of you, we are already working together on follow-up research proposals and I'm very much looking forward to it!

My thanks also to the international modelling teams, in particular to Dr Emma Terama, Dr Sen Li, Dr Anastasia Lobanova, Prof. Dr Tim Carter and Dr Stefan Fronzek, Dr Marianne Madsen, Prof. Dr Jens Christensen, Dr Rob Alkemade, Dr Lamprini Papadimitriou, Dr Andrea Roventini and Dr Francesco Lamperti, and all of the Italian modelling team. I'm sure we'll continue to work together! Thanks also to Dr Niki Frantzeskaki for introducing all of us to pathways and wild-cards!

Ein ganz herzliches Dankeschön an alle meine deutschen Kollegen und Freunde und ich Spreche hier nicht über meine geliebte NDH-Playlisten. Katharina Hölscher, ich schreibe dir auf meiner Lieblingssprache. Danke, meine Liebe. Wir sind “wie Blitz und Donner, wir sind gemeinsam stark... Das Schicksal wartet nur auf uns!” Katharina, ohne dich wäre all mein (PhD)Leben nicht so lebenswert gewesen. Danke, Dr Janina Onigkeit! Es war mir eine Freude, mit dir für unsere ‘fuzzy-sets paper’ zusammen zu arbeiten, auch in Kassel. Ich glaube, du bist eine wunderbare Person, außerdem bist du ein gründlicher Forscher. Vielen Dank Prof. Martina Flörke. Deine Neugier, effektive Führung, Einsichten und echtes Interesse, weißt du in lebhaften Diskussionen zu teilen. Ich hoffe wirklich, dass wir in Zukunft zusammenarbeiten werden! My thanks to all the archetype-analysis team, guided by Prof. Klaus Eisenack and Dr Christoph Oberlack. You opened a new world to further develop ‘my’ scenarios. Thanks also to all the Prospex team, led by Dr Marc Gramberger, Mrs Katharina Faradsch and Mr Stefan Haenen - though you are Flemish, Stefan, I know. It was a true pleasure to get to know you, and the world of post-its, stakeholder engagement and facilitation. I'm sure our roads will cross soon!

Of course, thanks to my fellow SGL-colleagues and wonderful support during this experience. Thanks to Prof. Dr Jakob Wallinga. Jakob, you supported my research since day one in spite of being very far from your expertise and I'm really grateful! Thanks to all the senior staff, particularly, Dr Jeroen Schoorl: I'll never forget the Andalusian-porra-geology course! Thanks also to Ms Mieke Hannink and the administrative support team.

A special thanks to the 'juniors'. Starting from my first room-mates, Jasper, Marijn, Jeppe and Fraser (a pity you left, but you really helped at the very beginning and it was nice meeting you both in Denmark and Scotland!). Thanks also to Maricke, Femke, Chantal, Kasia, Nienke, Luc, Alex, Yingxia and last but not least Selçuk. You made my PhD path lots of fun, with (too early!) morning runs, much-needed cafezinhos, trips and shared stories! Thanks to the Latin friends and colleagues, Arturo, Rafael, Marcos. Thanks for your genuine interest in my research, teaching with R, lively lunches and life in general. Muchas gracias tambien a Sarahi y Alvarito! I hope to work with you all in the future!

My existential friends, from a life-time. Moglio, grazie di esistere e di essermi sempre accanto, in ogni momento da più di 20 anni. E, ovviamente, non vedo l'ora di partire per la nostra prossima fuitina e continuare a crescere insieme! Dr Guimarães, Gordinho, obra prima, muito obrigada! Thanks for showing me the way, long ago in Brussels, that research can be a passion. Without you, I would have not known this world existed. Thanks to Ben. Heather, thanks to you and your lovely family, including also Riley, and so many very British moments in the Netherlands! And all my Wageningen-friends, Lingtong, Benjamin, Yorick, Danny, Line and many others. So nice to have you in my life!

Living abroad and using little social media means that I don't see some of my friends as much as I would love to, and sometimes loose contact. Special thanks to Prof. Mantelli at the University of Genova and Prof. Dr Kroeze at Wageningen University for being my academic inspiration during my Bachelor and MSc theses. Prof. Mantelli, Lei è l'incarnazione del talento universale, oltre che a essere una persona semplice e stupenda. Senza i Suoi insegnamenti, non sarei qui. Thanks to all my friends in Genova, Brussels, Italy, Brazil, China, Africa, Europe and the world. Places and times have changed so fast and drastically, that sometimes I feel I met you in different lives, but your love still supports me in good and difficult moments...this thesis is also for you!

Un enorme grazie alla mia famiglia. Grazie di tutto, davvero... e soprattutto per tutti i sacrifici affrontati in un mondo ostile! Un grand merci à toi aussi, Giulia! Peut-être tu comprendras parfaitement l'italien et donc... grazie per l'ispirazione che dai a tutti noi, con i sorrisi e il carattere deciso (chissà da chi hai preso). In qualche modo, sei riuscita a mettere assieme tutti i lati migliori della famiglia. Ook hartelijk dank aan de familie van Vliet voor jullie ondersteuning en positieve reacties tot alle keuzes die ik heb genomen.

Last but not least, gracias Wilbert, mi amor. Siempre me has amado y apoyado y nunca te asustaste de mis elecciones de vida, incluyendo mi gusto por la academia. Pasamos por mucho juntos, pero lo mejor está aún por llegar!

Summary

Climate change is one of the greatest challenges of our time and requires unprecedented changes to mitigate greenhouse gas emissions and adapt to climate-change impacts. However, different definitions of climate change are used by scientists, decision makers and stakeholders, making it a challenge for climate-change science to be credible, demand-driven and policy-relevant at the same time. These issues relate to (i) the ontology of climate change, i.e. its essence and its multiple drivers in the context of the anomalous speed of complex human-environmental interaction (the 'what'), and (ii) the epistemological challenges posed by the different knowledge systems, viewpoints and stakes that have evolved from an earlier dominant positivist viewpoint to the current post-modern and relativist viewpoints (the 'how').

In the context of this knowledge paradigm, the future is by definition unknown and unknowable. Climate-change scientists have to deal with a high degree of uncertainty about the future and a high level of complexity by structuring analysis with scenario typologies ad methodologies. The challenge of scenarios is to be scientifically credible (credibility) while at the same time reflecting different viewpoints (legitimacy) in order to be relevant for decision-making (salience). These three criteria are complemented with a fourth 'consistency' criteria, which evaluates scenario typologies (elaborated in Section 1.2) and their balance between credibility and legitimacy. The challenge of fulfilling these criteria is amplified by the lack of a clear goal and methodology for scenario analysis, which I address by classifying the typologies and methodologies of scenarios analysed in this thesis in the context of the state-of-the-art knowledge.

The overall research questions were developed to guide the operationalisation of the essence and definition (ontology) as well as knowledge paradigms (epistemology) of climate-change science through scenario analysis in four chapters. Firstly, I analyse scenario types (qualitative and quantitative) and identify the weak link between narratives and quantifications which still undermines the credibility and full consistency between qualitative and quantitative scenarios. I then address and analyse this link in **Chapter 2** by developing a fuzzy-set methodology. Secondly, I analyse scenarios across scales and identify the opportunities and limits of developing multi-scale scenarios with 'nesting' approaches, which undermines the balance between the credibility and legitimacy of

scenarios. I address this in **Chapter 3** by combining quantitative top-down scenarios with qualitative bottom-up scenarios. Thirdly, I examine the meaning of consistency across scenario scales and scenario types. I explore this with a scenario archetype analysis in **Chapter 4**. Fourthly, I analyse scenario goals and identify the problem that scenarios are generally developed to provide input to IAV and IAM studies, but not used to contextualise normative scenarios. I conclude by proposing that their salience could therefore be enhanced by identifying the users and the policy-questions that need to be addressed. The specific operationalisation is based on an analysis of capitals and capacities as a means to frame exploratory scenarios as the enabling or constraining socio-economic context for normative scenarios.

All the analyses presented in the chapters have been developed using the European and Central Asian versions of the global Shared Socio-economic Pathways (SSPs) and, to a conceptual extent, of Representative Concentration Pathways (RCPs), developed as part of the IMPRESSIONS project.

Chapter 2 focuses on the link between qualitative (narratives) and quantitative (input variables to integrated assessment modelling) scenarios by assessing the different uncertainties resulting from their inherent complexities. These complexities can be addressed in both narratives and modelling using a fuzzy-set methodology. This methodology makes it possible to build narratives and detail them quantitatively using the SAS approach, while simultaneously reducing subjective interpretation in the conversion between narratives and quantifications.

Chapters 3 and 4 discuss both the quantitative and qualitative scalability of the scenarios. In Chapter 3, I use an artificial-surface modelling framework to weigh the relative importance of demographic urban land-use drivers and combine them with bottom-up narratives from local (national, regional and municipal) case studies. In Chapter 4, using a qualitative archetyping approach, I classify all SSP narratives to assess divergences and similarities across the same scenario archetypes. The findings of Chapter 3 suggest that global and European scenario archetypes are consistent across scales, and that both downscaled scenarios and local stakeholder-led narratives contribute to the creation/formation of holistic scenarios of what drives the future of urbanisation in Europe. In Chapter 4, I conclude that archetyping scenarios by redefining global scenarios in contextualised scenarios reduces sources of inconsistencies. In both Chapters 3 and 4, the SSP with high challenges to mitigation and low challenges to adaptation (SSP5) tends to be the most extreme scenario (with skyrocketing GDP and high population growth) with a different magnitude of challenges across the European continent. In addition, the local versions of SSP5 tend to diverge from the global archetype more than the other SSPs. Chapter 5 provides a novel scenario angle. SSPs have been developed as 'exploratory scenarios', i.e. without explicit policy assumptions. At global scale, the link with policy assumptions has been developed with quantifications of land-use change and energy portfolio trends, together with policies on mitigation. Such scenarios are 'normative scenarios' that depict a choice of trajectories to match a defined goal such as emissions targets or measure the effects of policies, etc. In this chapter, I develop the conceptual link between exploratory and normative scenarios, and design the exploratory scenario to be the context for adaptation and mitigation. The exploratory scenarios describe the potential for societal transformation to enable change (actual transformation) in normative pathways. In the synthesis, I evaluate the analysis of Chapters 2 to 5. In Chapter 2, the fuzzy-set methodology contributes to credibility by strengthening and clarifying the link between narratives and quantifications. However, further broadening of the credibility criterion to include legitimacy in Chapters 3 and 4 highlights the emerging trade-off between legitimacy and credibility when bottom-up scenarios and worldviews are not adequately included. The archetype concept of Chapter 4 demonstrates that when scenarios diverge across scales, both scales and worldviews affect the scenario logic within the same archetype. The degree to which scenario narratives diverge from their corresponding archetypes reinforces the conclusion in Chapter 2 that both narratives and quantifications should be fully utilised to develop consistent and comparable scenarios that are capable of capturing the specific, context-relevant characteristics (legitimacy and salience).

If scenarios are consistent and balanced across top-down and bottom-up scenarios, as well as narratives and quantifications, then scenarios are also salient because they improve understanding of the future potential to achieve desirable futures by analysing real-world capacities, as analysed in Chapter 5. The definition of 'consistent scenarios' has been thus expanded to include the credibility, legitimacy and relevance criteria. The comparison across the SSPs demonstrates how the balance across the four criteria highlights different components when analysed together. For instance, credibility evaluates how 'scientifically sound', i.e. internally consistent and plausible, the scenarios are.

I highlight the importance of divergence in multi-scale scenarios, not only for specific context-bound drivers but also for others which are taken for granted in multi-scale scenario assessment. Such divergence arguably reflects different worldviews that challenge state-of-the-art knowledge and can ultimately question the role of global scenarios in guiding local scenario versions with a nested approach. Ontologically, redefining the climate-change challenge as a sustainability challenge has helped frame the SSP uncertainty space as one of challenges to transformation, rather than one of the challenges to mitigation and adaptation. Epistemologically, this challenge has implied the role of both narratives and quantifications to be equally important in capturing different uncertainties, stakes and worldviews.

Abbreviations

FCM Fuzzy Cognitive Map

GCM Global Circulation Model

IAM Integrated Assessment Model

IAV Impact, Adaptation and Vulnerability assessment

IPBES Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC Intergovernmental Panel on Climate Change

RCP Representative Concentration Pathways

SAS Story and Simulation

SSP Shared Socio-economic Pathways

STEEP Society, Technology, Economy, Environment, Policy

Contents

Chapter 1

Introduction

1.1 Climate-change science and exploratory scenarios

Climate change is one of the greatest challenges of our time (G20, 2009). Since the onset of climate-change science in the 1970s (Peterson et al., 2008) and politicisation of climate-change science (Weingart et al., 2000), scientists and policy makers now agree that action is urgently needed to mitigate greenhouse gas (GHG) emissions and adapt to climate change impacts (IPCC, 2014, 2018).

Translating such general agreement to a consensus on necessary action is less straightforward because different definitions of climate change are used by scientists, decision makers and stakeholders. Additionally, scientifically different perspectives emerge on how climate-change science can be at the same time scientifically credible and demand-driven and policy-relevant (Kunseler et al., 2015; Lourenço et al., 2015). These issues can be captured with two overarching questions: firstly, the essence of climate change (the 'what?') is still debated because climate change is a long-term, multi-faceted problem with multiple drivers, challenges and solutions (Geels et al., 2016; Feola, 2015). Secondly and related, different pathways span heterogeneous systems of knowledge, viewpoints and stakes (the 'how?') (Geels et al., 2016). The 'what' and 'how' questions are the guiding principle of this thesis. The introduction will, therefore, start with an introduction of what is the essence of climate change and how the knowledge in this field has evolved.

The discussion about the essence of climate change and its definition is an ontological question (i.e. what is climate change). In the last decades, the scientific debate has expanded from the original definition of climate change as a physical anomalous change in our climate due to increasing GHG emissions and accumulation in the atmosphere (Crutzen & Stoermer, 2000) into a debate of solutions and wider societal and environmental implications of policies aimed to mitigate and adapt to climate change (Wise et al., 2014). This expansion is reflected in the involvement of broader and more diverse disciplines: from the first seeds of the concept of Anthropocene in the late 1970s - 1980s, (paleo)climatology, geology, atmospheric chemistry and other natural sciences were involved in understanding the role and mechanisms of climate feedbacks (Hulme et al., 1999). As consensus grew stronger that humans were driving an unprecedented change, not only in the climate but in the whole environment, other scientific disciplines started to address the link between human activities and their impacts. In the last decades, increasing computing capacity has sped up both the representation of feedbacks between physical spheres (for example the atmosphere and the hydrosphere) in Global Circulation Models (GCMs) and incorporation of human activities and climate change in integrated, multi-sectoral modelling platforms, so-called Integrated Assessment Models (IAMs).

Scientific evidence is also growing around the anomalous speed of global change in both socio-economic and Earth Systems (Great Acceleration) (Steffen et al., 2004), which further connects human activities and impacts through feedbacks among climate, environmental and human systems (Fischer & Knutti, 2015). The magnitude of the Great Acceleration is concerning because of its association to adverse impacts, both observed and projected by IAMs. The ontological question of what climate change means needs to be placed in this complex human-environmental-interaction context. This implies that climate-change science needs to include different scientific disciplines.

Understanding 'how' climate-change science evolves and embeds different knowledge paradigms is an epistemological problem. As explained above, climate-change science currently covers many disciplines, uncertainties, values and stakes. In line with its ontological development, the climate-change paradigm has profoundly changed from an earlier dominant positivist viewpoint that climate change can be quantified and measured (for example by measuring GHG concentrations over time) to include more post-modern and relativist viewpoints that climate change is a multi-faceted reality told by different narratives (Geels et al., 2016). Under this paradigm, climate-change science needs to be not only sound and credible (for scientists of various disciplines) but also legitimately developed (by including other stakeholders) and socially and policy-relevant (by including decision makers). Crucial in relation to the epistemological issue is the acknowledgement that there are multiple knowledge holders that need to be involved in climate-change science.

An important component of climate-change science are scenarios that are developed to understand drivers or solutions to climate change. This forward-looking objective adds an additional layer of uncertainty to the (already) complex nature of human-nature interactions, because under the post-modern paradigm, the future is by definition unknown and unknowable. Therefore, climate-change science deals with both high uncertainty about the future and high complexity (Zurek & Henrichs, 2007). A common approach utilised to systematically explore the future is 'scenario analysis'. Originally, scenario analysis was not a scientific discipline but has developed from strategic military planning in the 1950s to become an independent set of tools and methodologies applied by many disciplines to systematically explore the future. To date, as a climate-change scientific approach, scenario analysis needs to be credible, but also legitimate and relevant. Scenario analysis is closely related to the epistemological and ontological issues.

This thesis aims at contributing to the climate-change scientific debate by using the ontological and epistemological issues not only as conceptual guide but also as starting points that can be operationalised with scenario analysis. In the next sections of Chapter 1, I first zoom on the criteria (credibility, legitimacy, consistency and salience) to evaluate and link epistemology and ontology with scenario analysis. I define the scenario approach utilised in this thesis in the broad context of state-of-the-art knowledge in the current scenario literature. Subsequently, I introduce the scenarios in the specific context of the IMPRESSIONS project, i.e. the context of the European case studies utilised in this thesis. I conclude Chapter 1 by introducing the research questions addressed by the analysis in Chapters 2-5 and a reading guide through the analysis to the synthesis. In the synthesis, I evaluate the analysis of Chapters 2-5 for scenarios to be not only scientifically credible, legitimate (i.e. inclusive of different values and narratives) and salient (i.e.relevant to decision making), but also *consistent* across epistemologies and ontologies. The consistency criterion is introduced in the next section as key to enable iteration between ontology and epistemology of climate change.

1.2 Criteria to evaluate progress on the ontology and epistemology of climate-change science

The ontological and epistemological climate-change-science issues are highly interdependent which calls for addressing them simultaneously. Changing knowledge systems and knowledge holders are involved in the process of determining the ontological question of what the future might look like and what needs to be addressed. This, in turn, shapes the source and nature of knowledge utilised to structure the study of the future. The conceptual view of ontological and epistemological issues in climate-change science are operationalised using the criteria of credibility, legitimacy and relevance (Cash et al., 2002) as widely utilised in the scenario literature (e.g., in the latest examples, Frame et al. (2018) and Cradock-Henry et al. (2018)). See also Kunseler et al. (2015) for examples from a participatory point of view and van Voorn et al. (2016) from a modelling assessment point of view. These three criteria are complemented with a fourth 'consistency' criteria, which evaluates scenario typologies (elaborated in section 1.2) and their balance between credibility and legitimacy. The criteria in Figure 1.5, adapted from Cash et al. (2002), are defined as follows:

1. **credibility:** scientific adequacy of the technical evidence and arguments
2. **legitimacy:** scenarios that consider stakeholders' divergent values and beliefs
3. **consistency:** quality and strength of links across scenario typologies in Figure 1.1, as a balance between credibility and legitimacy
4. **salience:** relevance of the scenario to the decision-makers' needs

The evaluation criteria are fundamental to ensure the delicate balance of scenarios to be, on the one hand, comparable and applicable in multi-sectoral assessment, capable to capture global drivers and therefore consistent with global scale assumptions and, on the other hand relevant and representative of multiple views to be embedded in local jurisdictions and decision making.

1.3 State-of-the-art of multi-scale scenario typologies and methodologies

The importance of the diverse attributes and goals of scenarios has lead to the fast development of a myriad of typologies and purposes. Together with the need to integrate different systems of knowledge to develop policy-relevant analyses, methodologies are manifold and diversified over the past 20 years. Although a comprehensive methodology and one classification do not exist, landmark papers (Van Notten et al., 2003; Börjeson et al., 2006) and the recent international science-policy assessments of IPBES (Ferrier et al., 2016) provide an up-to-date landscape of methodologies and classifications. Van Notten et al. (2003) recognise 14 scenario typologies which are based on three overarching themes: the project goal (i.e. exploration or decision-making support), the process design (intuitive or formal) and scenario content (complex or simple). Börjeson et al. (2006) classify scenarios on users' questions: 'what will happen?' (predictions or forecasts), 'what could happen?' (exploratory scenarios) and 'what do we want or should happen?' (normative scenarios). The IPBES scenario assessment (Ferrier et al., 2016) classifies scenarios according to four policy-making phases: (1) set the agenda to develop exploratory scenarios in qualitative form; (2) design policies by developing normative scenarios (i.e. alternative pathways to reach a desired endpoint); (3) analyse alternative policy-screening scenarios; (4) review the past policy effects and compare that to the desired endpoint of the scenarios. Figure 1.1 synthesises the vantage point for the scenarios developed and analysed in this thesis. These vantage points are the definition of 'goal', 'type' and 'scale' of the scenarios.

The first vantage point is the scenarios' goal. In this thesis, the goal is to *explore* alternative futures and, therefore, the scenarios' answer to Börjeson's et al. (2006) question 'what could happen'. However, even if the question is straightforward, a net division probably does not exist in practice as exploratory scenarios could also be used to identify targets and desirable futures (as will be described in Section 1.2.1). The second vantage point defines the methodology. This includes defining both scenario type and dimensions (the scenarios need to follow a rigorous scientific process, to be credible, but they also need to be relevant to decision making (Chaudhury et al., 2013)). In the literature (summarised in Figure 1.1), the most common classifications distinguish between qualitative and quantitative methodologies. Qualitative methodologies include narratives, videos and illustrations, while quantitative methodologies include numerical information based on, for example, models. The third vantage point is the scenarios' scale, which relates to its form and goal (Van Notten et al., 2003).

The three vantage points are iteratively approached in a scenario analysis. The scenarios' goal determines what type and scales need to be addressed. Conversely, the scale of analysis affects the type and even the scenarios' goal as an indicator of their feasibility

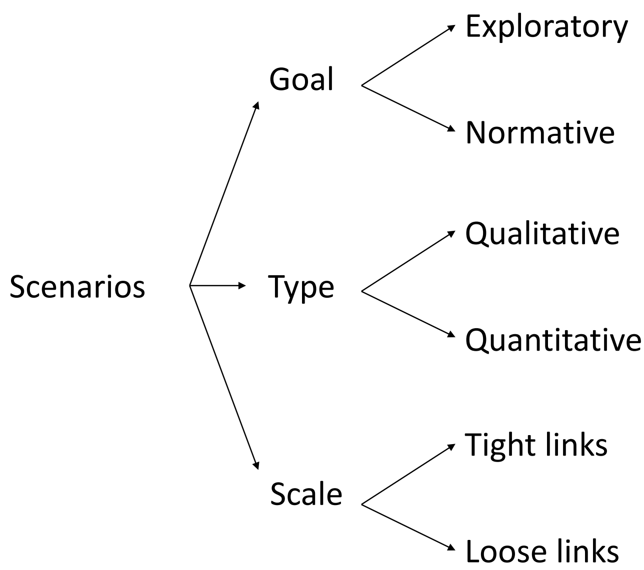

Figure 1.1: Updated macro-classification of socio-environmental and climate scenarios. Adapted from Van Notten et al. (2003), Börjeson et al. (2006) and Ferrier et al. (2016)

and desirability.

In the next subsections, I explore the state-of-the-art knowledge of how the vantage points polarities (e.g. normative, exploratory in Figure 1.1) are operationalised to discuss why scenarios approaches need to be redefined within the epistemological and ontological understanding of climate change.

1.3.1 Goal

Exploratory and normative scenarios: The scenarios' goal can be defined by their objectives, but also by their process and the question they address. In this sense, the international climate-change and environmental scenario community has generally focused on the question 'what could happen', at least at the first stage of any scenario process, whereas the regional and national communities have focused rather on the 'what should happen and how' questions. Although conceptually clearly distinct (Börjeson et al., 2006), the distinction between exploratory and normative has become less pronounced since the development of the latest global climate-change scenarios (Moss et al., 2010). These scenarios consist of three elements: the global Shared Socio-economic Pathways (SSPs); the Representative Concentration Pathways (RCPs); the Shared Policy Assumptions (SPAs). Given that the SSPs, RCPs and SPAs are defined as 'pathways' and not 'scenarios', the literature can clarify how do SSPs, RCPs and SPAs form scenarios and if a distinction between normative and exploratory scenarios can be made. A citation from O'Neill et al (2014) suggests that a pathway (SSP or RCP) combined with policy assumption (SPA) constitute a scenario:

> "SSPs include quantifications of factors that are considered drivers of such outcomes such as population growth and economic growth, but quantification of the consequences of these drivers is left to scenarios that will be produced based on the SSPs (van Vuuren et al., 2014). It is for this reason that the scenario framework distinguishes between "pathways", which describe one component (such as RCPs or SSPs) of integrated scenarios, and "scenarios" themselves, which combine pathways with other information such as emissions, climate projections and policy assumptions to produce integrated descriptions of future climate and human system development. It is these scenarios, rather than the SSPs themselves, that would be used to do analysis such as comparing outcomes in a policy scenario with outcomes in a reference (no-policy) scenario."

van Vuuren & Carter (2014) suggest that SSP and RCPs are considered scenarios, similarly to previous SRES scenarios. They, however, suggest that an SSP and an RCP can be combined in a single scenario (van Vuuren et al., 2012b), thus with or without a SPA:

> "the current paper concentrates on establishing linkages both within the new scenarios framework (relating SSPs and RCPs) and between the framework and the existing scenarios literature. This can then: (i) assist IAV researchers in using (elements of) existing scenarios in studies based on the new framework, and (ii) aid interpretation in assessments that compare findings using the new scenarios framework with results based on existing scenarios" and "It is only by combining RCPs with SSPs (thus reconciling the socio-economic and climate projections) in the next step of the process that coherent and integrated characterisations of the future can be crafted."

Also according to the IPCC glossary, from a content point of view, an SSP *is* the same as a socio-economic scenario:

> "**SSP:** Currently, the idea of shared socio-economic pathways (SSPs) is developed as a basis for new emissions and socio-economic scenarios. An SSP is one of a collection of pathways that describe alternative futures of socio-economic development in the absence of climate policy intervention. The combination of SSP-based socio-economic scenarios and Representative Concentration Pathway (RCP)-based climate projections should provide a useful integrative frame for climate impact and policy analysis."

> "**Socio-economic scenario:** A scenario that describes a possible future in terms of population, gross domestic product (GDP), and other socio-economic

factors relevant to understanding the implications of climate change."

Initially, the SSPs and RCPs have been developed as a 'parallel process' (Moss et al., 2010). One of the main reasons was pragmatic (i.e. a faster process to produce integrated scenarios). But other reasons include the fact that a one-to-one link between one SSP and one RCP does not exist (Ebi et al., 2014). Rather, one socio-economic future can lead to a range of different emission scenarios. This was new, because all previous scenarios consisted in pre-defined global associations of selected socio-economic and climate-change trends. Methodologically, the SSPs and RCPs were developed to be more flexible, and to be matched in a 'scenario matrix' (van Vuuren & Carter, 2014; van Vuuren et al., 2012a,b). In theory, any SSP could be matched with any RCP. Immediately after their publication, multiple combinations of SSPs and RCPs have been used, especially in regional IAV applications of this matrix (IIASA, 2013). The development of scenarios that contain global trends on energy and land-use and policy assumptions (e.g. SPAs) have only recently been published (Riahi et al., 2017). The SSPs have been designed by the international climate community for several applications, first and foremost as input to Integrated assessment models but also as regional, national and sectoral extensions in combination with (downscaled) RCPs (Absar & Preston, 2015). This was the case for the US SSPs (Absar & Preston, 2015), European SSPs (Kok et al., 2018)and (Tàbara et al., 2018), and European Coastal SSPs (Reimann et al., 2017), and West African scenarios (Palazzo et al., 2017) as in Figure 1.2. Such applications have utilised the SSPs and RCPs as 'exploratory' scenarios. Absar & Preston (2015) and Kok et al. (2018) downscaled the 'basic SSPs'. As with the IPCC SRES scenarios that preceded the SSPs, the global SSPs consist of narratives, qualitative tables and quantifications of key drivers.

Although recent application utilise also the SPAs to develop regional scenarios (Kebede et al., 2018), this thesis places itself in the regional sub-global extensions which start from basic SSPs to better utilise SSPs as exploratory scenarios.

1.3.2 Type

Scenarios can be developed in different forms depending on the goal of the scenario exercise. Quantitative scenarios are generally computed by expert-developed models and, as such, they are regarded as more transparent than qualitative scenarios because the underlying assumptions are, in principle, explicitly specified and documented in variables or parameters (Alcamo et al., 2006). Quantitative scenarios can be limited to a subset of assumptions and can be based on models that represent only one viewpoint about how the world works (Alcamo & Henrichs, 2008), posing a risk that users may misinterpret such seemingly precise quantitative information. In contrast, qualitative scenarios can incorporate multiple points of view (especially when stakeholders are involved) and can potentially better capture complex behaviours of the system. The involvement of

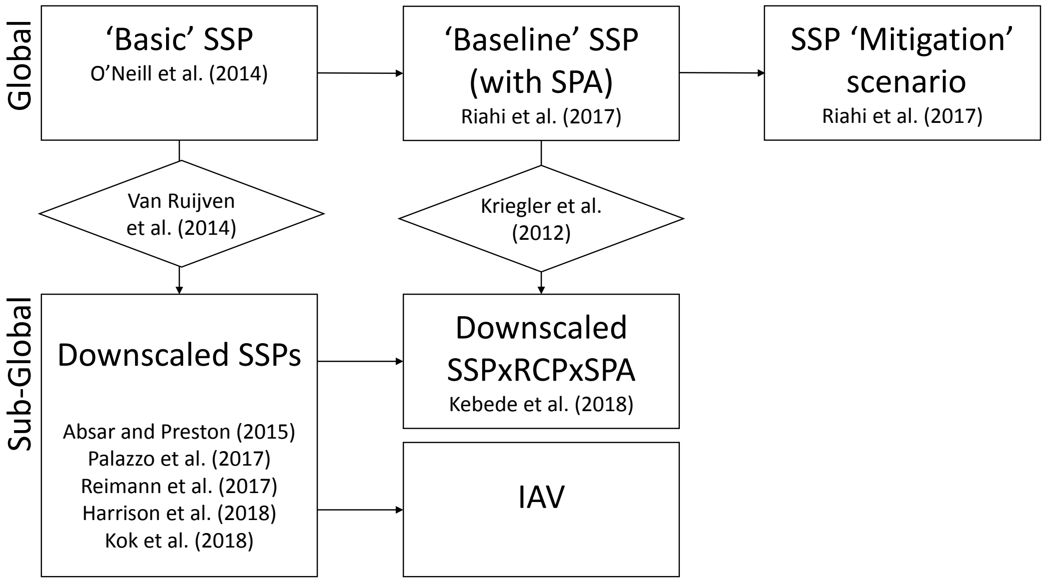

Figure 1.2: Overview of utilisation of Shared Socio-economic Pathways (SSPs) in the impacts, adaptation and vulnerability (IAV) community. SSPs can be combined with Representative Concentration Pathways (RCPs) and Shared Policy Assumptions (SPAs)

stakeholders also increases scenario salience and legitimacy (Cash et al., 2003; Rounsevell and Metzger, 2010). A trade-off, however, is that underlying assumptions tend to remain implicit and difficult to test, whilst the lack of quantification can also add to subjectivity and lower credibility (Alcamo and Henrichs, 2008; Alcamo et al., 2006).

A common practice consists in combining both quantitative and qualitative scenarios to have scenarios which incorporate the advantages of both. This practice is systematised in the so-called Story and Simulation (SAS) approach. As the name suggests, this approach involves the development of both scenario narrative and quantifications. A key element is the *iteration process* to ensure consistency, at least in theory. In practice, the short-comings of SAS have been identified as the conversion between qualitative and quantitative scenarios and the reproducibility of the results.

Although SAS is still used, especially in global scenario exercises, the sub-global community is developing alternative methodologies which move beyond SAS. The iteration element is complemented, or substituted, by increasing the structure of the qualitative elements (for example, with Morphological Analysis, Fuzzy Cognitive Maps, and CIB) directly applicable for quantification, or by developing direct quantifications with Bayesian statistics approach.

In this thesis, I start from the assumption that narratives and other qualitative scenario products are a fundamental part of the scenarios and that narratives should be linked *'better'* to quantifications (Chapter 2), rather than structured more. The implication is that narratives and quantifications can still be developed separately, using different methodologies and in separate moments. But to develop a systematic link, the nature of narratives and quantifications need to be unravelled. The goal of better linking narratives and quantifications is ultimately to maintain the richness and diversity of the scenario products. This stems from utilising different sources of knowledge, while having a comprehensive and *consistent* final product.

The choice to maintain diverse scenario products also affects multi-scale scenario methodologies. For instance, by combining participatory approaches with IAMs, different dimensions can be explored. This affects also the overall goal and nature of the scenarios. Also the methodology is affected with different sources of knowledge to allow and demand different strengths of links across scales.

1.3.3 Scenarios across scales

Fundamental in (exploratory) scenario development is the fact that drivers that act over a range of scales are brought together. This has resulted in 'scale' being an essential notion in scenario development. As mentioned in Chapter 4, the concept of 'scale' stems from its early system theory conceptualisation in the ecology hierarchy theory developed in the 1980s by Allen and colleagues (Allen & Starr, 1982; Allen & Hoekstra, 1992). According to this theory, elements of complex systems are organized hierarchically based on multiple spatio-temporal and functional scales. Linkages within and among socio-economic, political and biogeochemical systems (Gallopín et al., 2001, Gibson et al., 2000) have evolved also in scenario exercises, since at least the 2000s with the MA sub-global scenario assessments. In landmark papers on multi-scale linkages, reasons to develop linked scenarios include stakeholders engagement, cross-scale interactions highlighting and better understanding of impacts due to socio-economic, political and natural (e.g., climate and ecological) processes at different scales (Kok et al., 2007, Biggs et al., 2007). Scenarios can be 'loosely linked', developed at several scales simultaneously and then linked (for example by up- or down-scaling) a posteriori, or 'tightly linked' and developed iteratively. In the literature, these two typologies are referred to as 'multi-scale' and 'cross-scale scenario' (Biggs et al., 2007; Scholes et al., 2013). To date, truly cross-scale assessments are still rare (Scholes et al., 2013). However, the number of multi-scale scenarios is increasing with the aim to better understand the interactions of processes at different levels and scales (van Ruijven et al., 2014). Although different degrees of linkages are possible, depending on their desired outcome and purpose (Biggs et al., 2007, Zurek and Henrichs, 2007), the multi-scale scenarios are being operationalised as 'nested scenarios' (Absar & Preston, 2015) with Schweizer & Kurniawan (2016) defining them as:

> "outcomes for a country within a region within a global context"

In this definition, global scenarios (both in narrative and quantitative form) are used as boundaries for downscaled regional quantifications. The global scenario input is then 'linked' with local narratives and quantifications, often with a participatory process. The persisting subjectivity of this linking process, as well as what tightly or loosely linked scenarios means, has been recently questioned and addressed in several analyses. Firstly, by taking a step back to analyse the original meanings of 'equivalence', 'consistency' and 'coherence' across scales, as originally defined in Zurek & Henrichs (2007) and Biggs et al. (2007), in Kok et al. (2018) and Chapter 4. Secondly, by systematically structurally defining key qualitative elements to be 'consistent' across scales (Schweizer & Kurniawan, 2016). Thirdly, by explicitly linking bottom-up and top-down approaches (e.g. Absar & Preston (2015); Nilsson et al. (2017); Kebede et al. (2018)). In all cases, the overall approach consists in applying global scenarios (SSP RCP SPA framework) either directly or downscaled regionally with both qualitative and quantitative elements nested from global to regional scale. This thesis develops from this context and explores links across scales in both qualitative and quantitative elements. Special focus is given to the aspect of *consistency* across scales and across qualitative and quantitative scenarios in all chapters. Importantly, also in this thesis, scenarios are classified as 'multi-scale', although cross-scale elements in the regional scenarios are also explored.

1.4 Context of the methodology

1.4.1 The IMPRESSIONS project and case studies

A specific context and application to the scenarios developed in this thesis is necessary to understand scenario elements that are not analysed in the next chapters but that are relevant to understand both state-of-the-art and what the scenarios want to achieve. These elements are the normative scenarios, the detailed process of the SAS approach, as part of collaborative efforts amongst scientists and stakeholders, and the description of the case studies, within a larger European project of which the work in this thesis was part.

The specific context is the IMPRESSIONS project (http://www.impressions-project.eu/), a 5-year, 11 million Euro collaboration between 25 partners in 16 countries across Europe. The IMPRESSIONS project's objective is to identify robust solutions for Europe under high-end (between 2°C and 6°C T increase in 2100 relative to 1850-1900) climate-change and socio-economic scenarios. The specific ontological aspect in IMPRESSIONS is the assumption that high-end scenarios and their adverse impacts are still plausible, and therefore scientific efforts need to identify and promote robust solutions, by exploring normative pathways from high-end impacts towards achieving a desired future.

The overall methodology of IMPRESSIONS to achieve this objective is the project's most innovative element of integration across disciplines. Although the initial design depicted the SSPs and RCPs as conform to SRES scenarios, SSPs and RCPs have been extended within the case studies to co-create qualitative and quantitative knowledge about alternative 'high-end' futures for impact, adaptation and vulnerability assessment with a novel combination of approaches. Normative scenarios, which consist of bundles of actions and strategies towards reaching a sustainability vision, are not only a 'parametrisation of the SSPs and RCPs', but consist of full societal contexts which describe the enabling conditions and constraints to achieving a desired end-goal (vision). The IMPRESSIONS methodological novelty to linking SSPs and RCPs with normative pathways consists in developing and applying cutting-edge interdisciplinary and trans-disciplinary methodologies to develop multi-scale scenarios. The multi-scale (exploratory) scenario development process resulted from collaboration among IMPRESSIONS partners and is part of this thesis in the form of both input data and goal of the scenarios.

This thesis, as part of the implementation of IMPRESSIONS, has performed the following tasks, which provide the input to the analysis of this thesis:

1. Operationalise SAS in workshops with a flexible structure with stakeholder, facilitators of the participatory process and case-study leaders (input to Chapter 1, section 1.3.2)
2. Operationalise the fuzzy-set methodology in the participatory process to strengthen the link between scenario narratives and quantified scenarios. The scenarios were developed in collaboration with stakeholders, case-study leaders and impact modellers (input to Chapter 2)
3. Develop a multi-scale modelling framework to quantitatively analyse the socio-economic and/or climate change cross-sectoral impacts and vulnerability. The urbanisation quantitative scenarios, part of this thesis, were developed in collaboration with modelling teams (input to Chapter 3)
4. Develop a multi-scale narrative for each SSP in the participatory process to contextualise the global SSPs. The match between global and local narratives was developed in collaboration with social scientists, stakeholders and facilitators of the participatory process (input to Chapter 4)
5. Develop the multi-scale quantitative and qualitative multi-scale scenario to contextualise normative scenarios in collaboration with natural and social scientists, modelling teams, stakeholders and facilitators of the participatory process (Chapter 5)

The five steps of collaboration listed above were carried, as part of a multi-scale framework, with five case studies (Figure 1.3) chosen to represent different levels of aggregation, availability of information and policy-relevant sectoral foci. The five case studies are :

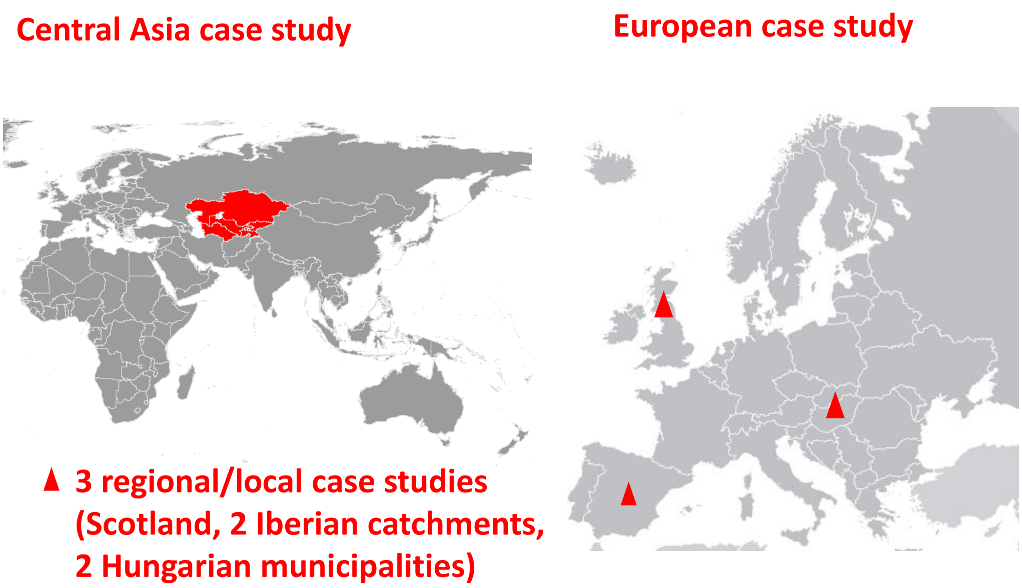

Figure 1.3: Geographical distribution of the five IMPRESSIONS case studies

Central Asia as a pivotal region between Russian and Chinese powers and their sphere of influence on Europe; Europe (28 EU countries + Norway and Switzerland); three local case studies: Scotland, the trans-boundary Tagus-Segura and Guadiana river basins in Iberia and Veszprém and Szekszárd municipalities in Hungary (Figure 1.3).

The European and local case studies reflect the diversity of the European continent. It ranges from the sub-arctic climate of northern Scandinavia to the Mediterranean climate of southern Europe, and from wide lowland plains to high mountains, with a mix of land-uses including expanding urban areas, intensive arable and horticulture, extensive upland grazing and forestry. Climate and socio-economic change are therefore likely to have different impacts across Europe on social and economic sectors, human health, ecosystems and the goods and services they provide. Central Asia case study focuses on the relation between five countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) and on the region as a sphere of external political influence on Europe. In this case study, the scenarios have the objective of exploring and analysing the impacts in the water, agriculture, energy and trade sectors to understand the indirect impact on stability and trade in Europe.

Exploratory scenarios have been developed in all IMPRESSIONS case studies. Multi-scale modelling allows for higher scale models (e.g. global) to provide information on boundary conditions for lower scale level models (e.g. European/national). For example, global trade flows at the global scale can provide the basis for understanding food imports to the European region, or European-wide human migration patterns may affect population change at the national and sub-national scale. The multi-scale approach also supports a comparison of model outputs across geographic scales for similar parameters. Similar to the modelling, the global narratives contextualise the lower-scale narratives. Compared to multi-scale modelling, the narratives also enrich the global SSPs. However, because the SAS process was designed to be also context specific, local narratives could also diverge from the global and European-wide narratives. Importantly, the Central Asia case study is consistent with both global and European scenarios, although it may deviate from global scenarios as local case studies would.

1.4.2 Operationalise Story and Simulation: truly bridging scenario narratives and quantifications across case studies

The SAS approach implies that models and narratives are two main products that need to be combined in an iterative procedure. Its implementation consists in stakeholder participation to the scenario production process (i.e. co-production) of qualitative and quantitative scenarios in 10 steps, as described in Alcamo et al. 2008. Scenario narratives and quantifications were developed for each case study following a decision tree that summarises the navigation between Steps 2-10, taking into account whether relevant scenarios already existed and also the different spatial scales of the case studies (Figure 1.4). The Pan-European and Scottish case study scenarios had been partly developed within a previous project (CLIMSAVE), while the Central Asian, Iberian and Hungarian case study scenarios were developed from the input provided by stakeholders in workshops.

For each case study, after the narratives had been formulated and considered satisfactory, selected variables were quantified for modelling purposes. As only a limited amount of time was available within the workshops (or expert meetings for the Scottish and European case studies), the maximum number of model variables that could be quantified with the aid of stakeholder input was limited to three or four.

The selection of these modelling variables was based on meeting a number of practical requirements. Firstly, the variables needed to reflect the expertise of most of the invited stakeholders and at the same time, reflect the key issues of the particular case study. Secondly, the variables should provide guidance for the quantification of a much wider range of socio-economic variables to be used within more general meta-models.

In addition to the model variables, the stakeholders were also required to help in the quantification of four types of socio-economic 'capitals' (human, social, manufactured and financial). Capitals are useful indicators of the overall wealth in a society, vulnerability of the system and ability of the society to adapt to changing circumstances (Gramberger & Watson, 2013). The full 10 steps implemented in IMPRESSIONS are described in the IMPRESSIONS Information Hub (http://www.highendsolutions.eu/).

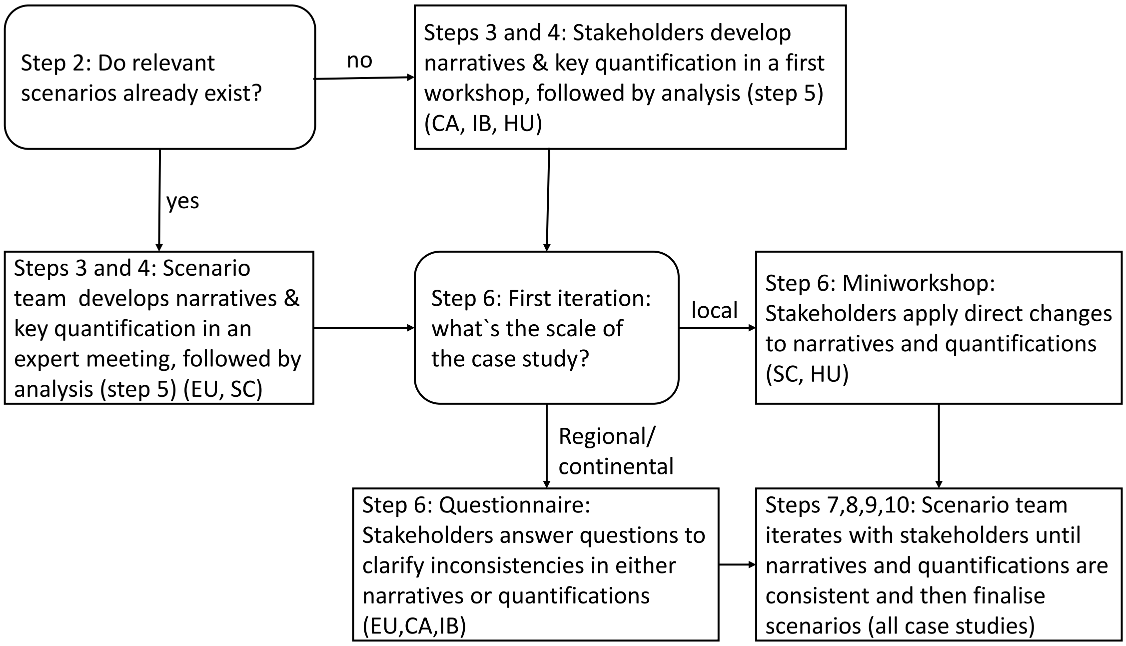

Figure 1.4: Decision tree for the steps to develop scenarios in all IMPRESSIONS case studies (EU= Europe, CA= Central Asia, IB= Iberia, SC=Scotland, HU= Hungary)

1.5 Problem statement: what contributions are the scenarios expected to make to climate-change science?

The ontological and epistemological background of IMPRESSIONS is well embedded in the post-modern knowledge paradigm: the identification of solutions to high-end climate change requires a highly interdisciplinary and transdisciplinary approach. The scenario typologies introduced in Section 1.3, while providing an orientation in the state-of-the-art scenario typologies and methodologies, also highlight the lack of a definitive approach to assess the criteria of credibility, legitimacy, consistency and salience of the scenario typologies.

This section addresses this shortcoming, by structuring the main challenges of operationalising the criteria in four main points:

- 1. Scenario types: The weak link between narratives and quantifications still undermines the credibility and full consistency between qualitative and quantitative scenarios. Considering that progress has been made towards improving *structure* in narratives (Kok, 2009; Kok et al., 2014) or qualitative trends (Schweizer & O'Neill, 2014; Carlsen et al., 2016) to better link to quantitative scenarios, this thesis applies a different angle according to which narratives should not be better structured but linked as *wholes* to convey all the potential that narratives can offer to the final scenario product. The specific operationalisation to strengthen and clarify this link, analysed in Chapter 2, consists of the bridge between a fuzzy-set methodology (to represent qualitative scenarios) and probabilistic methodology (to represent quantitative scenarios)

- 2. Scenarios across scales: multi-scale scenarios tend to be developed with 'nesting' approaches. While the advantages are enormous and allow to have consistent scenarios across different scales and case studies, their legitimacy is often questioned because multi-scale scenarios do not cover all the possible views, especially if these are inconsistent scales and mismatch global assumptions. The specific operationalisation to strengthen the link across scales consists in comparing modelling downscaled assumptions and stakeholders' assumptions to inform the future of urbanisation in Europe (Chapter 3). This implies also the importance of qualitative scenarios in informing the final message derived from downscaled scenarios.

- 3. Consistency across scales and scenario types: Because of the first two problems, a re-definition of what scenario *consistency* means is necessary by assessing consistency both across scenario scales and scenario types. Because, in both typologies, consistency has been prioritised with quantitative scenarios, this thesis develops the concept of archetype utilising the Cultural Theory, to complement existing assessments of what consistent scenarios mean.

- 4. Scenario goals: While scenarios are generally developed to be quantified in either IAM or IAV assessments, they are not used to contextualise normative scenarios. The criterion towards addressing the scenario goals is thus to evaluate their salience, by identifying who are the users and what policy-questions need to be addressed. The specific operationalisation is carried out by analysing capitals and capacities to frame exploratory scenarios as the enabling or constraining socio-economic context for normative scenarios.

1.6 Objective and Research Questions

The objective of this thesis is to develop socio-economic scenarios by applying novel methods, and to evaluate them using four criteria that operationalise the guiding concepts of ontology and epistemology. The following research questions (RQs) are addressed as in Figure 1.5:

- RQ1 (Chapter 2): How can different types of knowledge be linked in exploratory scenarios?

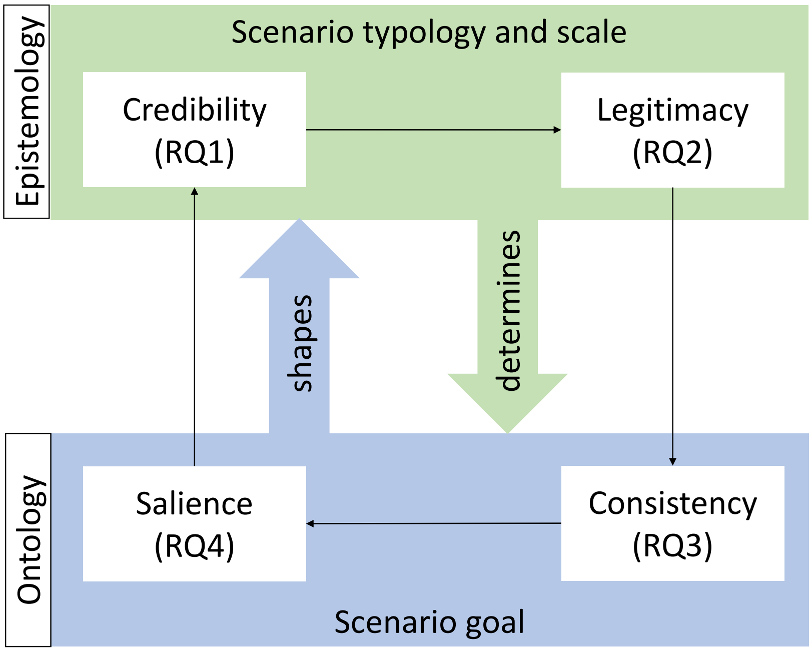

Figure 1.5: Four evaluation criteria to iteratively link progress on ontology and epistemology of climate-change science utilising scenario analysis. Updated from Cash et al. (2002)

- RQ2 (Chapter 3): What are the implications of matching top-down model-led quantitative knowledge and bottom-up stakeholder-led qualitative knowledge in multi-scale exploratory scenarios?
- RQ3 (Chapter 4): How does archetyping scenarios frame global top-down and local bottom-up scenario narratives?
- RQ4 (Chapter 5): What is the role of exploratory scenarios to improve understanding the future potential to achieve desirable futures and address the challenges ahead?

1.7 Reading guide of thesis chapters

Figure 1.6 guides through the content of the next chapters (2 to 6), to understand how the chapters lead to synthesis discussion on the criteria to evaluate how the scenarios have operationalised the ontology and epistemology of climate-change science. Chapter 2 (Ch2 box in Figure 1.6) sets the basis for Chapters 3, 4, and 5 (Ch3, Ch4, Ch5) with the hypothesis that scenario narratives should not be analysed solely as qualitative versions of model variables. Their application should be enhanced beyond communication purposes. Therefore, Chapter 2 argues that narratives and quantifications are inherently different, as they belong to different epistemologies, and therefore cannot be reduced but understood and linked within the different uncertainties they represent. Because of this link, multi-

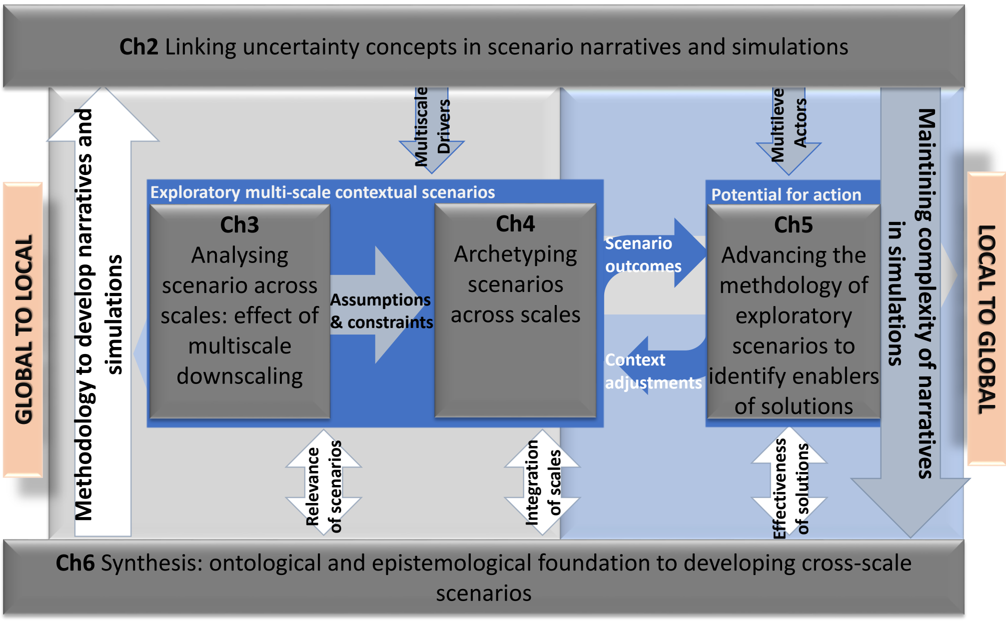

Figure 1.6: Conceptual linkages across the 4 analysis-chapters (Chapters 2-5) and the synthesis (Chapter 6)

scale scenario drivers need to be analysed in both qualitative (with qualitative knowledge such as multi-scale actors) and quantitative form (with quantitative or semi-quantitative form, i.e. scenario drivers).

In Chapters 3 and 4, the focus is on multi-scale drivers analysis in the context of exploratory scenario analysis. In Chapter 3, qualitative drivers and quantitative drivers are analysed to address understand what processes are captured when assumptions on key drivers (GDP and population) are linked across scales. Chapter 4 complements this analysis by utilising the concept of archetypes to link local and global scenarios and analyse cross-scale consistency. Albeit with novel approaches, Chapter 3 and, to some extent, Chapter 4 analyse scenarios from the perspective of scenarios as exploratory analysis of future drivers of climate change.

Chapter 5 develops a novel approach to scenario analysis to ontologically understand the nature of climate change as symptom of societal problems and worldviews (also addressed in Chapter 4). In this perspective, the role of narratives as holistic scenarios is fundamental in that they provide key information on what actors and what role they might play in the future.

Chapter 6 (Ch6 in Figure 1.6) reflects on the evaluation of scenario analysis in Chapters 2-5 according to criteria of credibility, legitimacy, consistency and relevance.

Chapter 2

Bridging uncertainty concepts across narratives and simulations in environmental scenarios

This chapter is based on:
Pedde, S., Kok, K., Onigkeit, J., Brown, C., Holman, I., & Harrison, P.A. (2018). Bridging uncertainty concepts across narratives and simulations in environmental scenarios. *Regional Environmental Change*, 1-12. doi: 10.1007/s10113-018-1338-2

Abstract

Uncertainties in our understanding of current and future climate-change projections, impacts and vulnerabilities are structured by scientists using scenarios, which are generally in qualitative (narrative) and quantitative (numerical) forms. Although conceptually strong, qualitative and quantitative scenarios have limited complementarity due to the lack of a fundamental bridge between two different concepts of uncertainty: linguistic and epistemic. Epistemic uncertainty is represented by the range of scenarios and linguistic variables within them, while linguistic uncertainty is represented by the translation of those linguistic variables via the fuzzy set approach. Both are therefore incorporated in the models that utilise the final quantifications. The application of this method is demonstrated in a stakeholder-led development of socio-economic scenarios. The socio-economic scenarios include several vague elements due to heterogeneous linguistic interpretations of future change on the part of stakeholders. We apply the so-called 'Centre of Gravity' (CoG) operator to defuzzify the quantifications of linguistic values provided by stakeholders. The results suggest that, in these cases, uniform distributions provide a close fit to the membership functions derived from ranges of values provided by stakeholders. As a result, the 90% or 95% intervals of the probability density functions are similar to the 0.1 or 0.05 degrees of membership of the linguistic values of linguistic variables. By bridging different uncertainty concepts (linguistic and epistemic uncertainties), this study offers a substantial step towards linking qualitative and quantitative scenarios.

2.1 Introduction

The drivers of climate change within socio-ecological systems, such as land-use change and greenhouse gas emissions, alter anthropogenic and climatic pressures in the systems (Schröter et al., 2005; Folke, 2006; Holman et al., 2016). The interconnectedness of these drivers adds uncertainty to our understanding of recent climate behaviour and future climate-change projections, impacts and vulnerabilities. Such uncertainties have often been accommodated using scenarios to systematically answer "what-if" questions (van Ittersum et al., 1998; Zurek & Henrichs, 2007; van Vuuren et al., 2012a). Unlike predictions and forecasts, scenarios do not imply a probability or likelihood (van Vuuren et al., 2012a). Instead, scenarios have been defined as "plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces" (Alcamo et al., 2005). As such, scenarios can be in quantitative (numerical) and qualitative (narrative) forms (Bambergerl, 2000; Philcox et al., 2010).

The complementarity of qualitative and quantitative scenarios is considered a potential strength in addressing complex problems (Vermeulen et al., 2013) since the so-called story and simulation (SAS) approach (Alcamo et al., 2006) became mainstream in scenario development (Kok, 2009). SAS consists of a ten-step approach aimed at developing and translating (often stakeholder-led) narratives into (often scientist-led) model quantifications, iterating and revising them until they are linked (van Vliet et al., 2010). SAS yields credible, plausible and innovative scenarios because of the inclusion of expert models combined with other creative elements introduced by stakeholders (Alcamo & Henrichs, 2008). The co-production also ensures consistency between stakeholders and model results (Kemp-Benedict, 2012; Schweizer & Kriegler, 2012). The final scenarios are more relevant and legitimate for end-users as stakeholders can identify their views (i.e. stakes) in the narratives.

Although conceptually strong, operationalising SAS has issues. Alcamo (2008b) already identified two SAS pitfalls: the 'reproducibility' and 'conversion' problems. The 'reproducibility' problem exists because assumptions and mental models are not explicit when a scenario narrative is developed, whereas the 'conversion' problem exists because narratives cannot be directly translated into quantifications. Moreover, the distinction between the two problems is often not straightforward. For example, fuzzy cognitive maps (Kosko, 1986), recently applied by Kok (2009) and Van Vliet et al. (2010), 'map' variables and connections by assigning a weight to each connection. In the literature, this method has been described as improving the structure and reproducibility of qualitative scenarios (Alcamo, 2008) and has been applied as a conversion tool between qualitative and quantitative scenarios (Mallampalli et al., 2016). Nevertheless, most state-of-the-art studies have tended to focus on addressing the 'reproducibility' problem as evidenced by the proliferation of systematic stakeholder-based modelling (Voinov & Bousquet, 2010), whilst studies focusing on the 'conversion' problem show methodological trade-offs between model compatibility, stakeholder expertise and development of narratives (Mallampalli et al., 2016). Hence, further studies addressing the 'conversion' problem are urgently needed. However, in order to tackle the 'conversion' problem in SAS, there is a need to take a step back, i.e. to better understand the gaps in knowledge within both qualitative and quantitative scenarios separately, before combining them (van Vliet et al., 2010). Scenario narratives integrate imagination in strategic thinking and combine short-term preoccupations in long-term planning with analytical thinking and creative visioning (Rasmussen, 2005). Because narratives provide 'holistic views' of the future and transcend the sum of single parts (Rasmussen, 2005), it becomes very complex to reduce narratives to a selection of model variables. Whilst acknowledging this gap, we argue that narratives can be bridged to models, while maintaining their original characteristics.

In SAS, two sources of uncertainty matter, epistemic and linguistic uncertainties (Regan et al., 2002; Uusitalo et al., 2015) (Figure 2.1). Epistemic uncertainty is due to imperfect knowledge about something that is theoretically knowable. In statistical models, epistemic uncertainty is further distinguished from aleatory uncertainty that relates to irreducible and unavoidable variation in stochastic processes (Uusitalo et al., 2015). Statistical models represent uncertainty "in terms of (aleatory) probability distributions and (epistemic) parameters" (O'Hagan et al., 2006). Linguistic uncertainty is inherent to our natural language and includes vagueness and ambiguity. Here, we categorise aleatory uncertainty as part of a broader 'epistemic uncertainty' category (Regan et al., 2002) and distinguish it from 'linguistic uncertainty'.

2.2 Material and methods

2.2.1 Developing participatory scenarios

The socio-economic scenarios analysed in this paper are developed within the EU-funded IMPRESSIONS project (Harrison et al. in review). The objective of the scenarios is to provide the context to understanding future impacts, adaptation and vulnerability to climate change at different scales in Europe. Because of their geographic breadth and narrative and quantitative character, the IMPRESSIONS scenarios can be applied to test the fuzzy sets methodology and compare the results across heterogeneous stakeholder groups. The IMPRESSIONS scenarios were intended to directly inform numerical inputs to a European-scale model known as the Integrated Assessment Platform (IAP) (Harrison et al., 2015), with the scenario-specific default values and uncertainty ranges of model inputs being derived from the stakeholder inputs. The quantifications derived from stakeholder input explicitly recognise both linguistic and epistemic uncertainty, in that

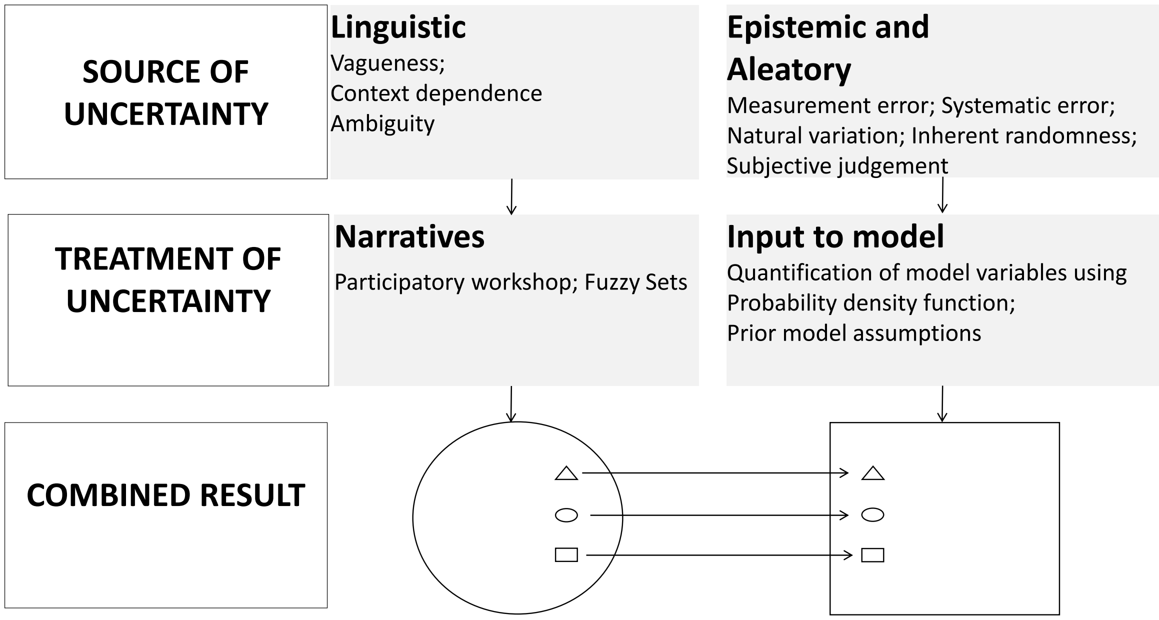

Figure 2.1: Conceptual framework (Background adapted from: (Regan et al., 2002)).

the stakeholders intended the ranges (and the scenarios within which they occur) to allow for epistemic uncertainties in the quantities described (section 2.1.1), while the fuzzy-set and probabilistic interpretation accounts for linguistic uncertainty (sections 2.2.1 & 2.2.2).

The results discussed in this paper are based on scenario quantification for five case studies which cover Europe and Central Asia: Europe as a whole (Europe) (Kok et al., 2018); Central Asia (Central Asia); Scotland (Scotland) consisting of national scale scenarios for Scotland; Iberian river basin scale scenarios (Iberia); and Hungarian municipality level scenarios (Hungary). For the Central Asia, Iberia and Hungary case studies, heterogeneous groups of stakeholders were engaged. For Europe and Scotland, scientists acted as stakeholders to modify a set of existing stakeholder-developed scenarios (Harrison et al., 2013, 2015). In this paper, we refer to these scientists as 'expert stakeholders'.

Producing narratives and quantifications in a participatory scenario process

Stakeholders were invited to produce narratives and key quantifications in a two-day workshop within each case study. Stakeholders were selected to cover a wide range of expertise on different sectors and to have different age, country, and educational backgrounds (see Gramberger et al. (2015)). All scenario products were produced by stakeholders as the result of different workshop processes which alternate brainstorming sessions in groups with plenary discussions, called the STIR approach (Gramberger et al., 2015). The approach is designed such that both narratives and key input quantifications become intrinsically connected by having the same mix of facilitators and stakeholders producing both scenarios and quantifying key drivers. Such an approach is fundamental for consistent co-production of both narratives and quantifications.

The workshop process consists of three main components. In the first component, stakeholders are guided to list, discuss and select key uncertainties relevant to all scenarios and further develop narratives for each individual scenario. In the second component, narratives are discussed in groups (group exercise), where stakeholders are asked to provide qualitative (linguistic) trends for key variables in a written questionnaire. The variables' descriptions are presented to stakeholders without rephrasing the modellers' wording to avoid misinterpretation. The third component consists of an individual exercise, where each stakeholder provides their personal opinion on what quantitative ranges represent those qualitative trends.

Given inevitable time constraints and the importance of completing all steps within the workshop, the maximum number of variables that could be quantified by stakeholders was limited to three or four. These variables were selected based on two criteria. First, the variables had to reflect the expertise of most of the invited stakeholders, and nest well among the key issues for the case study. Second, the variables should relate to model input parameters that were among the most sensitive in the model. For the Europe case study, the results of a full sensitivity analysis of the IAP (Kebede et al. 2015) were available to support the choice of sensitive variables. In addition, stakeholders provided qualitative guidance to inform the quantification by the modellers of a much wider range of socio-economic variables used within the impact models. For example, stakeholders provided trends for four capitals (human, social, manufactured and financial) of resource availability (Porritt, 2007) to be applied to model vulnerabilities to climate change (Dunford et al., 2015). This paper only analyses the trends for the stakeholder-quantified variables, therefore analysis of capital trends is excluded.

Together with trends and quantification of variables, stakeholders were asked to provide an indication of their confidence when quantifying each variable, to have qualitative information on the stakeholders' professed confidence levels about the quantifications. The question asked to both stakeholders and expert stakeholders after the quantification of each variable was 'How confident are you for the quantification you provide for this variable based on your background knowledge (0-10)? (0=not confident; 10=very confident)'. We classified the data in four categories to analyse a qualitative 'confidence index'. The sample was not suited to infer statistical conclusions: firstly, the sample size was too limited due to resource limitations; secondly, the motives behind confidence levels cannot be assessed; thirdly a psychological and cultural analysis on the background of the stakeholders is out of the scope of this analysis. We therefore decided to analyse the confidence index qualitatively. The analysis of this index occurs according to one of the main assumptions introduced in this study, i.e. that incorporating a subjective level of confidence could alter the value or weight of quantification (Van der Sluijs, 2007). In the next section, we explore how to proceed with quantification of a given variable using the ranges provided by stakeholders during a facilitated workshop. We use the variable 'Change in food imports from 2010' for Europe case study as an example to follow the methodological steps and to illustrate the results of other linguistic variables.

2.2.2 Addressing the 'conversion' problem: quantification of narratives

Measuring vagueness using fuzzy sets

Vagueness in stakeholder-driven scenarios exists because each stakeholder could have a different interpretation of the linguistic term 'high increase' in food imports compared to 2010. To measure this vagueness, each stakeholder was asked to define what he/she personally meant by 'high increase' by providing a numerical range. The analysis of ranges derived from stakeholder values assumes that each stakeholder has a different, but equally valid, interpretation of the same statement due to different backgrounds, beliefs, knowledge, and so on.

Numerical ranges provided by each stakeholder can be represented with fuzzy numbers in a membership function (see, for example, Cornelissen et al. (2001)). According to fuzzy logic, 'high increase' is a vague statement that should be addressed in a mathematical form (Zadeh, 1975b,a), i.e. by quantifying the degrees of membership rather than assessing the likelihood or frequency of the linguistic term 'high increase'. By providing a range for the linguistic term 'high increase', stakeholders estimate the vagueness of the linguistic term, thus addressing linguistic uncertainty. All the individual ranges constitute the input of each linguistic value for each linguistic variable (Figure 2.2).

We define the analysed variable a 'linguistic variable' with a 'linguistic value'. A linguistic value is the vague analogue of a numerical value and is the imprecise non-numerical value of a linguistic variable (Zadeh 1975a). Linguistic variable and model variable have the same meaning to reduce the risk of misinterpretation, which means that the model variable is presented to stakeholders as such in the form of a linguistic variable, without reducing or simplifying the meaning of the original model variable.

A linguistic variable can have several linguistic values. In our example, linguistic variable 'Change in food imports from 2010' has five linguistic values ranging from high 'decrease' to 'high increase' (Figure 2.3). The purpose of the linguistic values is to inform the calculation of fuzzy membership functions that will be used as model inputs. The membership function of a linguistic variable $\mu\_\tilde{A}$ assigns a numerical value to each range (x), depending on how much the range 'belongs' to its linguistic variable. For instance, in (Figure 2.2) we assume that all ranges of a linguistic variable belong in a space included

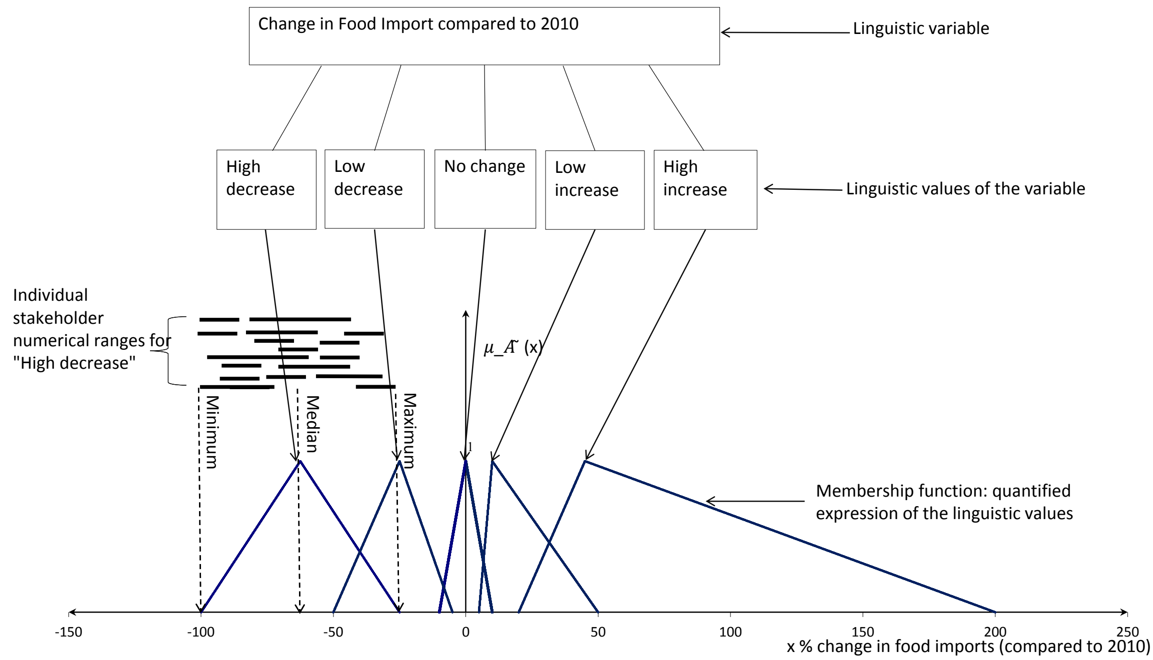

Figure 2.2: Representation of the linguistic variable 'Change in Food Import compared to 2010' and its linguistic values, together with the numerical ranges provided by each stakeholder for a linguistic variable and the fuzzy restrictions. Membership functions define the degree of membership ($\mu\_\tilde{A}$ in y-axis) of fuzzy numbers in a 0–1 scale. Adapted from (Zadeh, 1975a)

within the median, which belongs completely to the linguistic variable $\mu\_\tilde{A}$ (x_median)=1, and the maximum and minimum of the ranges, which belong least to the linguistic variable $\mu\_\tilde{A}$ (x_(min,max))=0.

The last step is the defuzzification of the linguistic value using one of various existing operators. The operator used here is the centre of gravity (CoG) (Figure 2.3), a continuous defuzzification operator, which means that small variations in an input should result in small changes in output values (Leekwijck and Kerre 1999). The centre of gravity of the membership function is defined in equation 2.2.2 by the minimum, median and maximum values of each linguistic value obtained from the results of the entire stakeholder group (Kok et al., 2014). The CoG was selected because it represents the most "central" value between the membership function's minimum, median and maximum and therefore was considered a better indicator of higher likelihood than the median, which is more sensitive to intermediate values. However, the disadvantage is that the CoG is more sensitive to changes in extreme ranges, compared to other metrics such as the mode or median.

$$CoG(x) = \frac{(min + median + max)}{3} \tag{2.1}$$

The CoG provides the basis for converting the qualitative changes into quantitative changes for each scenario, as described below. The quantified changes are then run in the

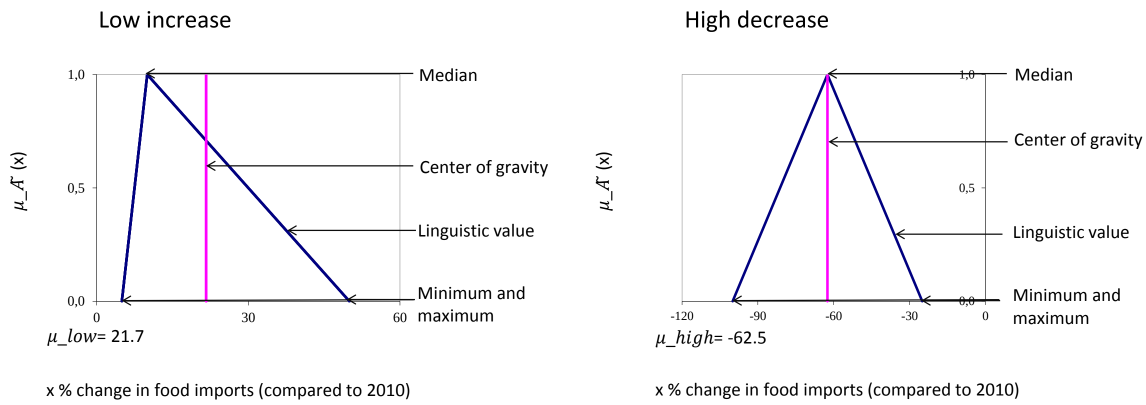

Figure 2.3: Defuzzification of the linguistic values 'high decrease' and 'low increase' for the linguistic variable 'change in food import compared to 2010'. Defuzzification is made with the centre of gravity method

.

IAP. The uncertainty around these changes is handled as set out below.

Probabilistic interpretation of vagueness

The scenario quantification in the IAP recognises both epistemic uncertainty and the validity of each stakeholders' perspective on future changes through the derivation of probability density functions for each model input. For each linguistic value of each linguistic variable, the CoG represents the single output of a fuzzy set. We define the CoG as the default value of the membership function. The variation in values around this default value is taken to define the linguistic uncertainty, which must be taken into account in subsequent analysis (modelling) steps. Generally, this can be achieved by representing the variation as a probability density function (PDF), allowing the form and range of the stakeholders' quantification to be retained, and also allowing parameter sampling for rigorous sensitivity or uncertainty analyses. Ideally, the form of the PDF will be derived from the frequency of values suggested by stakeholders, with Gaussian and uniform distributions offering particularly useful and contrasting alternatives. However, in many cases the appropriate function is not clear, either because of an asymmetric or multimodal frequency, or because inadequate frequency data are available. In these cases, it may be preferable to define discontinuous probabilities that minimise the need for additional assumptions to be made. In the case of the IAP, input parameter values were assigned different (linguistic) ranges: a 'credible' range within which the 'default' value occurs and a wider 'possible' range. Assuming a probability distribution for the CoG, we define, for each linguistic variable, a 'default', a 'credible' and a 'possible' range. Beta distributions are often chosen in the literature when non-normality is assumed due to their flexibility and limited ranges (Brown et al. 2014); however, they are not universally appropriate. For consistency with previous work, we use beta-distributions here, but fitted distributions all had a low alpha and beta (between 1 and 2), suggesting that uniform distributions may have provided alternative adequate fits.

Fitting of the distributions to each linguistic variable's CoG was carried out with an online tool that requires a scaled [0,1] modal value and 10% or 90% limits (Brown et al. 2014). The CoG was therefore scaled as in equation 2.2):

$$ScaledCoG(x) = \frac{(median - min)}{(max - min)} \tag{2.2}$$

This scaled CoG value was defined as the modal or 'default' value, with the 90% range taken to define the 'credible range' and the 95% range taken to define the 'possible range'. This choice is based on previously selected confidence ranges with the IAP (Brown et al., 2014) and on expert judgement on the distributions fitted to the data obtained by stakeholders, but other choices would have been equally possible.

2.3 Results

2.3.1 Addressing the 'conversion' problem: quantification of scenario trends and input to the Integrated Assessment Platform

As the CoG consists of the defuzzification of a single linguistic value, defuzzifying all linguistic values of a given linguistic variable is necessary to quantify the scenario trends until 2100. To exemplify this, we follow on from the example used in the Methods section of the linguistic variable 'Change in food imports compared to 2010 [in %]'. For this linguistic variable, we have defuzzified five linguistic values: 'high increase' has a CoG of 88%; 'low increase' has a CoG of 22%; 'no change' has a CoG of 0%; 'low decrease' has a CoG of -27%; and 'high decrease' has a CoG of -63% (Figure 2.4). These values are then applied according to the scenarios generated by stakeholders. For example, based on the narrative for the European SSP1 scenario, the expert stakeholders were asked to draw qualitative trends for the variable 'Change in food imports compared to 2010 [in %]'. They decided that the trend should be a 'low increase' in 2025, then a 'low increase' in 2055 and finally a 'high decrease' by 2100. With defuzzified values: in the future scenario

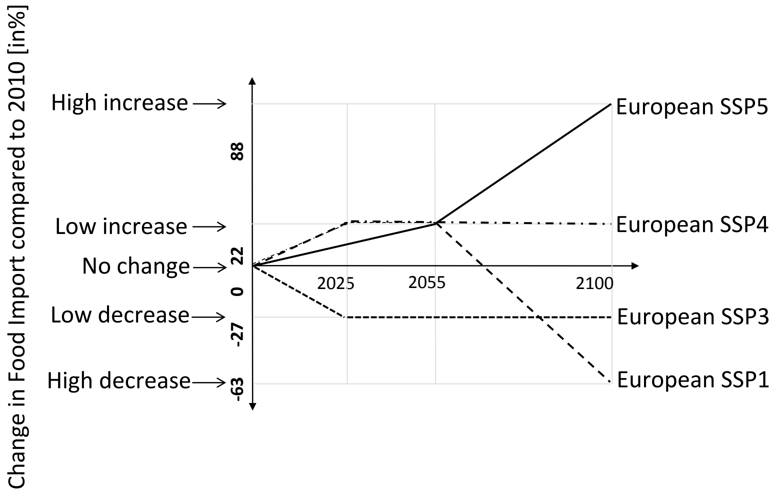

Figure 2.4: Quantification of the centre of gravity for the five linguistic values (high decrease–low decrease–no change–low increase–high increase) of the linguistic variable 'Change in Food Import compared to 2010 [in%]'. Four future trends are shown for the European Shared Socio-economic Pathways

European SSP1, food imports in Europe will be 22% higher in 2025 compared to 2010 and then remain constant at 22% higher in 2055, before decreasing to -63% by 2100 compared to 2010 levels (Figure 2.4). These values for each SSP, based on the CoG of each linguistic value, represent the default input values for the impact models used in the case studies analysed.

The results suggest that the distribution fitted to the scaled CoG (interpreted as the mode of the distribution) is close to a uniform distribution. Based on an assumption of quasi-uniformity (i.e. apparent but not precise uniformity), the PDF ranges resulted in similar ranges to the membership functions for all quantified IAP variables. 90% of the PDF was thus close to a 0.1 degree of membership and 95% of the PDF was close to a 0.05 degree of membership in the fuzzy set function (Figure 2.5). The quasi-uniform distributions suggest the possibility of fuzzy numbers to directly provide all IAP input ranges (default, credible and possible) and to account for nearly all ranges by stakeholders by staying very close to the min and max of the fuzzy number (up to 0.05 membership). From a conceptual perspective, the quasi-uniformity is also consistent with our assumption of allowing stakeholders to define the likelihood of their quantifications by providing a 'range' instead of a 'most likely value' of each linguistic value and a 'confidence' index; presumably this also suggests substantial uncertainty across stakeholders where wider ranges result from more stakeholders being included.

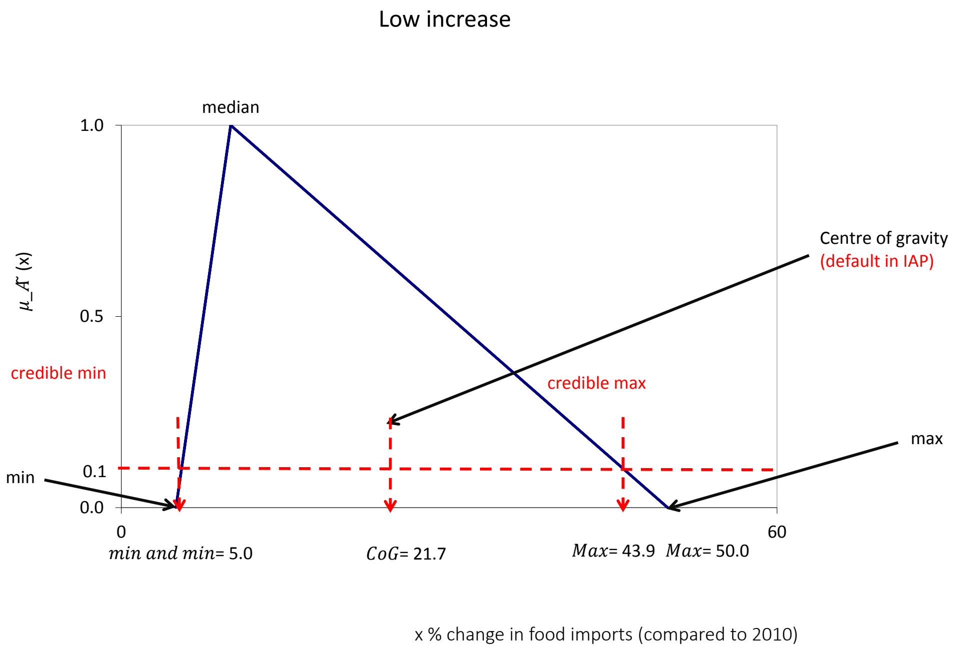

Figure 2.5: Visualisation of 'default' and 'credible range' for the integrated assessment platform using stakeholder-derived quantification

2.3.2 Analysis of assumptions in quantifications of scenario trends

To test whether uniformity could be the best assumption, we accounted for and qualitatively analysed the performance of the 'confidence' index that the stakeholders and expert stakeholders provided with their quantification of the linguistic values for each single linguistic variable. Three possible interpretations of the results were considered: a) stakeholders, aware of their insufficient background knowledge, provide 'very unlikely' values and a low 'confidence' index or b) stakeholders provide what an expert would consider a 'reasonable or realistic' estimate and are either 'confident' or 'less confident' or c) stakeholders under- or overstate their expertise.

The qualitative analysis of the 'confidence' index supports our choice of a uniform-like probabilistic representation of likely values for two reasons. Firstly, we observed similar patterns in the 'confidence' index across the same case study rather than for the same variable. For example, confidence is generally lower for Europe and Scotland case studies compared to Central Asia, Hungary and Iberia. Stakeholders and expert stakeholders all tended to provide a similar confidence level independent of the variable, and thus independent of background knowledge. Secondly, we found no obvious correlation between 'reasonable' quantifications and the 'confidence' index for stakeholders or expert stakeholders: low confidence may indicate lack of knowledge in cases where unrealistic ranges were provided, or may indicate a critical attitude when reasonable ranges were provided. With the information available, however, we cannot infer whether, and how

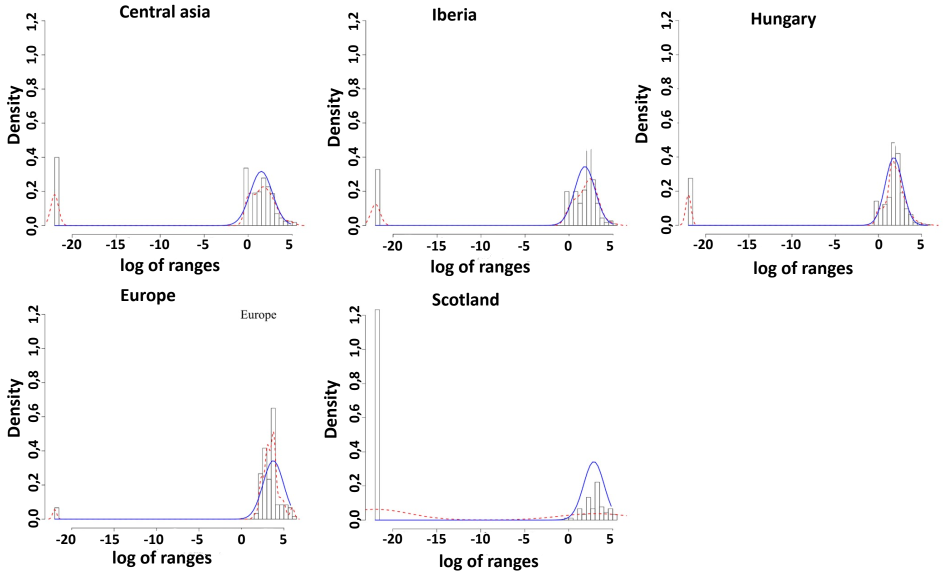

Figure 2.6: Log of ranges for all linguistic variables for five case studies. The blue line is the theoretical normal distribution for all ranges (excluding single values, in the leftmost column) and the red-dotted line is the empirical distribution following all linguistic values. Linguistic value ranges for Europe and Scotland were quantified by expert stakeholders, while linguistic value ranges for Hungary, Iberia and Central Asia were quantified by stakeholders

much, cultural and other personal factors (such as a critical attitude or understanding of the exercise) played a role in the ‘confidence’ index.

Ranges provided by stakeholders and scientists acting as stakeholders (‘expert stakeholders’) were also compared across case studies (Figure 2.6) to understand whether minima and maxima values could lead to different distributions (e.g. multimodal or particularly skewed for either stakeholders or expert stakeholders).

From a qualitative point of view, the analysis did not show any specific pattern in either stakeholders’ or expert stakeholders’ ranges. The mean and standard deviation of ranges are higher for the more extreme linguistic values of the variables (i.e. ‘high decrease and high increase’). The ‘confidence’ index seems to be inelastic to variation in ranges, narrower ranges being associated with greater confidence. For example, both Scotland case study expert stakeholders and Central Asia stakeholders did not provide ranges for one linguistic value but rather gave single values (represented by the leftmost column of each graph in Figure 2.6), but Central Asia stakeholders produced more extreme values than those provided by Scotland case study expert stakeholders. Central Asia stakeholders and Scotland case study expert stakeholders scored differently in the ‘confidence’ index, though they had similar ‘confidence’ in providing quantifications for the same variables (GDP and population trends). The 'confidence' index also differed between expert stakeholders. Europe case study expert stakeholders provided the least '0' range values and Scotland case study expert stakeholders provided the most '0' range values (Figure 2.6). Assuming that scientists possess the background knowledge for the model input quantification, such difference in ranges may indicate the preference of some scientists to provide the most likely value instead of a range.

2.4 Discussion

Our analysis demonstrates and applies a method to translate vagueness to probabilities as a double-edged sword that will improve current practice when operationalising the Story-And-Simulation approach, while also improving statistical and fundamental understanding of how uncertainties are perceived and dealt with.

To this end, we addressed linguistic and epistemic uncertainties by 'bridging' them, rather than attempting to reduce them because the narratives provide 'holistic views' of the future that the models could not fully capture. In our approach, both narratives and models still remain 'black boxes' (see the round and squared shapes in Figure 2.1) throughout our analysis and neither the linguistic uncertainties of the narratives nor the epistemic uncertainties of modelling are reduced but 'bridged'. However, effective methods do exist to unravel the single 'black boxes'. These methods have the advantage of adding structure to either narratives or both narratives and models (see for example the Cross-Impact Balance approach for narratives in Schweizer and Kriegler (2012) or Fuzzy Cognitive Mapping to link narratives and models in van Vliet et al. (2010)). However, these methods do not yet address the different uncertainties and are less transparent or too complicated to carry out in stakeholder workshops.

We chose to represent the stakeholders' fuzzy numbers with uniform-like distributions for input in the IAP to avoid adding further assumptions and unintended interpretation. However, we provide a description of stakeholder ranges to enable a qualitative comparison with direct quantification of stakeholder-led narratives by impact modellers (Figure 2.6). This analysis shows that linguistic values in all case studies lead to different PDFs. In the Hungarian case study, Gaussian probabilities could approximate distributions reasonably well, in most cases, once the '0' values (or zero uncertainty) were removed. We interpreted this result as supporting the idea that stakeholders themselves can 'bridge' linguistic and epistemic uncertainty within the fuzzy sets approach. Stakeholders may provide reasonable ranges and could substitute expert judgement from impact modellers, at least for selected variables.

In sections 2.1 and 2.2, we have introduced the assumption that direct quantification of stakeholder-led narratives by impact modellers could add 'assumptions on assumptions', and fail to simply translate uncertainties, if impact modellers solely rely on their own ad-hoc judgements (Mallampalli et al., 2016) or simply misinterpret stakeholders‘ reasoning and opinions. Impact modellers are well experienced in addressing epistemic/aleatory uncertainty but address linguistic uncertainty less systematically (Regan et al. 2002). We tested this assumption by qualitatively comparing trends of stakeholders' and expert stakeholders' ranges across case studies. Instead of comparing trends across case studies, an alternative approach could have been to make single assumptions about interpreting all variable ranges in terms of PDFs, or different assumptions for each variable. But, after preliminary screening of the results, and due to the different types of variables analysed, a direct comparison among similar variables was not possible due to the limited number of participants and variables. Alternatively, a quantitative analysis can be useful to validate the use of stakeholder-led quantifications from a modelling output perspective. For example, Monte Carlo sampling from the PDFs generated for sensitive variables like GDP, population and food imports (Kebede et al., 2015; Brown et al., 2014) could be performed to analyse the propagation of uncertainty in impact models of both stakeholder-led input uncertainty around the CoG and PDFs generated by direct quantification of stakeholder-led narratives by impact modellers.

We have also assumed that, even if probability-based quantification is highly appropriate given the inevitable approximations, there is no further information that can be introduced to define the form of the PDF. In contrast, mainstream alternatives generally structure both narrative and quantification assumptions using probabilistic methods based on Bayesian statistics, such as Bayesian Networks (e.g. Henriksen and Barlebo 2008) and Bayesian reasoning (Kemp-Benedict 2013). We concluded that both methods would have been either incomplete or misleading in our analysis. Bayesian-based methods can structure uncertainties more transparently with both prior and posteriori distributions that quantify changing assumptions with acquired information. However, even such methods can be problematic if 1) little agreement exists on the source of the data – especially in data scarce case-studies such as Central Asia and 2) if participants have different expertise. Our qualitative analysis of the 'confidence' also shows that stakeholders' and scientists' (expert stakeholders) assumptions may be very different and difficult to predict. Even in 'expert stakeholders' participatory contexts, extra assumptions need to be minimised.

We suggest to further consolidate these results with a quantitative uncertainty analysis from the IAP output perspective and efforts to strengthen the input from a stakeholder workshop perspective. The stakeholders appreciated the usefulness of this exercise and generally agreed that stakeholders can help modellers in quantifying key scenario drivers. However, some stakeholders found the exercise difficult and this may have resulted in the generation of 'outliers'. Nonetheless, 'outliers' were included in the quantification of the CoG simply because we interpreted them as extreme values or ranges, consciously provided by the stakeholders. We limited ourselves to the exclusion of physically impossible values.

The most important exception was the quantification of GDP for the Central Asia case study. Here, extreme growth trends resulted in two very extreme scenarios. When faced with a choice between their quantification and model-led trends, stakeholders chose the (very extreme) trends resulting from their quantification. In such case, a compromise had to be made by applying the trend provided by stakeholders at the upper limit of what the models could represent. As suggested also by the confidence index analysis, however, there could be different but equally legitimate reasons for stakeholders to provide their trends. To reduce 'outliers' in future exercises, we suggest to improve the participatory process, at the root of this quantification, by better adapting questionnaires and processes to the stakeholders involved in the workshop, e.g. by including a formal stakeholder-mapping exercise prior to the workshops, to address uncertainty about the representativeness of stakeholders.

2.5 Conclusions

The fuzzy sets method has been recognised as a simple and transparent method (Alcamo 2008b; Kok et al. 2014; Houet et al. 2016) to be applied from global to local case studies, despite room for further improvement from stakeholder engagement perspectives. This analysis, based on the assumption that stakeholder values are the best available (or at least better than some poorly-defined combination of stakeholder and modeller inputs), is the first to show that stakeholders can provide reasonable ranges and that these can be used without adding further assumptions. Ongoing studies applying stakeholders' quantifications with fuzzy sets within impact models (e.g. Li et al. 2017) will further explore this potential in different modelling environments, aiming at a universally accepted tool to produce quantifications from narratives. Even though a formal validation step may lead to changes in the method, the core steps described are transparent and can be reproduced by practitioners in the field in any workshop settings.

At an epistemological level, this analysis contributes to enhanced dialogue and understanding between modeller-led and local, stakeholder-led communities, and linkage of qualitative and quantitative approaches by bridging the different uncertainty concepts (linguistic and epistemic and aleatory uncertainties) addressed by their research questions. We therefore did not simplify the relevant uncertainties (e.g. combining fuzzy logic and probabilities), but created a common, systematic language between the two communities. We further hope that our research will raise more attention to fundamental issues of different sources of uncertainty in participatory scenario development.

Chapter 3

Analysing scenarios across scales to project population and urban land-use in Europe to 2100

This chapter is based on:
Pedde, S., Clarke, E., Rounsevell, M., Terama, E. (2018). Analysing scenarios across scales to project population and urban land-use in Europe to 2100. *Submitted to Population and Environment*

Abstract

We explore the effect of demography on urban land-use in Europe using multi-scale scenario assumptions. The focus is on interrogating the consistency of assumptions developed at multiple scales and their effect on urban land-use. The methodology builds on the analysis of European Shared Socio-economic Pathways (SSPs) of artificial surface projections. The SSPs include (1) trends on total population, life-cycle and aging, and fertility and (2) European scale narratives of residential preference and mobility. The modelled SSPs are also combined with bottom-up qualitative SSP narratives. In all scenarios, the driver trends of residential preference and population are very diverse. However, the results for 2100 show a maximum increase of 20% in artificial surface in Europe, compared to baseline, in three out of four SSPs (SSP1, SSP3, and SSP4). Only in SSP5, increase will be >150%, due to strong preferences for green and coastal area, economic growth and urban sprawl. On one hand, our findings suggest a strong dependency between key modelling outcomes and demographic assumptions, especially assumptions on fertility in SSP5. On the other hand, we suggest that pan-European scenarios alone do not include all drivers and stakeholder-led narratives may provide the necessary contextual data. For example, on the mobility and migratory trends that can capture the complexity of socio-economic scenarios. These findings interrogate well-established assumptions in the urbanisation modelling literature, such as the preference for urban compact development in sustainable scenarios, and the relative weight of fertility versus migration, for some European regions. Our results suggest that pan-European modelling results provide a consistent approach to compare scenarios, but also need careful interpretation, in view of all the assumptions, to convey the best possible knowledge.

3.1 Introduction

Over the last two decades, global scenarios have developed to become instruments to inform policy on environmental and sustainability problems at global scale (van Vuuren et al., 2012a) but also at sub-global scale. The environmental and sustainability problems analysed at sub-global scale are land-use, climate-change impacts and adaptation (van Vuuren et al., 2010), structured in the form of scenarios, i.e. consistent narratives about how the future might unfold. A recent example of such global scenarios are the global Shared Socio-economic Pathways (SSPs), a set of five socio-economic scenarios covering the space of uncertainty across the challenges to mitigation (high for SSP3 and SSP5 and low for SSP1 and SSP4) and challenges to adaptation (high for SSP3 and SSP4 and low for SSP1 and SSP5). A fifth scenario, the SSP2, is located at the intersection of the other scenarios, and therefore covers medium challenges to both mitigation and adaptation (O'Neill et al., 2015, 2017). Compared to other existing global scenarios, the SSPs are designed to be implemented in analyses of land-use change impact and vulnerability at sub-global scales and provide boundary conditions as they account for a variety of potential changes in the socio-economic context (van Ruijven et al., 2014). An accepted finding is that sub-global assessments of land-use change generally consist of modelling tools developed to spatially downscale coarser global scenarios (Sleeter et al., 2012). The advantage of downscaling (coarse) global data is to provide gridded data to develop transparent scenarios, consistent with the original data and across scenarios (van Vuuren et al., 2010). Although the importance of socio-economic change to land-use change scenarios has been highlighted (Harrison et al., 2018; Holman et al., 2005), demographic assumptions are generally developed at the global scale (van Vuuren et al., 2010) and successively downscaled. For example, Terama et al. (2017a) and Terama et al. (2017b) have proposed an urban modelling approach which utilises sub-national downscaling of detailed population projections to regional level, and the translation of the downscaled projections into population structure driven by urban land use development up to 2100. The study suggests that given the predicted future changes to the demographic profile of Europe, in particular, an ageing population, strengthening the link between urbanisation trends and population structure is increasingly important. These results support the hypothesis that demographics is the major driver of urbanisation (Gonçalves et al., 2017; Nilsson et al., 2014) and therefore approaches are needed that analyse the effects of multiple aspects of demographics on urbanisation. For instance, urban sprawl is directly related to both a changing population structure (i.e. the total population and its age profile) and societal preferences. These, in turn, are determined by the socio-economic context, in regard to the residential preferences of the population and planning legislation. In addition to demographics it‘s important to recognise the importance of wealth (sprawl) and land-use policy in encouraging or constraining urban development (Reginster & Rounsevell, 2006). Because of the complexity of the interaction of drivers, which act at multiple scales, the use of either local data or global downscaled scenarios only, is not enough to fully capture urban land use dynamics. Demographic change, future urbanisation trends and the construct of these, must be analysed in their local (national to sub-national) socio-economic contexts. However, an advantage of having pan-European, top-down data is that population development is connected in a spatially-consistent way across regions. Cross region consistency could, for example, account for the connectivity between regions arising from population mobility (Reginster & Rounsevell, 2006; Rounsevell et al., 2012). Bottom-up approaches are also important since they can account for local contexts such as differences in land use planning policy that is implemented locally, but also influenced by national and subnational governance structures. The bottom-up is also important in accounting for the role of baseline urban patterns. Decisions by people about where to live are influenced by the current urban pattern and this varies across different regions. For example, Fontaine et al. (2014) demonstrated how people at different stages in their life cycles have different preferences for living in urban areas, peri-urban areas or rural areas. The legacy of urban development has created very different urban patterns in, for example, Hungary rather than Scotland, or Iberia and this will influence future urban development patterns (Li et al., 2016). In this paper we highlight where caution is required when interpreting consistent down-scaled scenario data, and explore where assumptions inherent in global scale scenarios may influence regional scale models in perhaps surprising ways. We explore the effect of using multi-scale scenario assumptions of demographic change using two methodologies, i.e. downscaled quantifications and bottom-up qualitative trends, to discuss the relevance of the assumptions developed at multiple scales.

3.2 Material and methods

The methodology consists of a multi-scale framework that links both qualitative and quantitative scenario products across scales (Figure 5.3). We use the Shared Socio-economic Pathways (SSP), which are qualitative and quantitative scenarios with assumptions on demographics, human development, economy, policies, technology and environment (O'Neill et al., 2017). The SSP scenarios are translated into two parts. The first part consists in the translation into pan-European and local narratives, described in Section 3.2.1. The European narratives are developed for Europe as whole, similarly to the global SSP narratives. The local narratives represent different geographic and socio-economic context, i.e. Scotland as a whole, Hungary with a focus on local municipalities and Iberia with a focus on Spanish/Portuguese river basin context. The second part consists of the translation into demographic scenarios, with quantitative trends on fertility, mortality and migration classified according to baseline fertility rates and income (KC and Lutz, 2017). Even if all European countries considered in this study are low fertility (fertility rate <2.9), European countries are subdivided into three regions: the countries

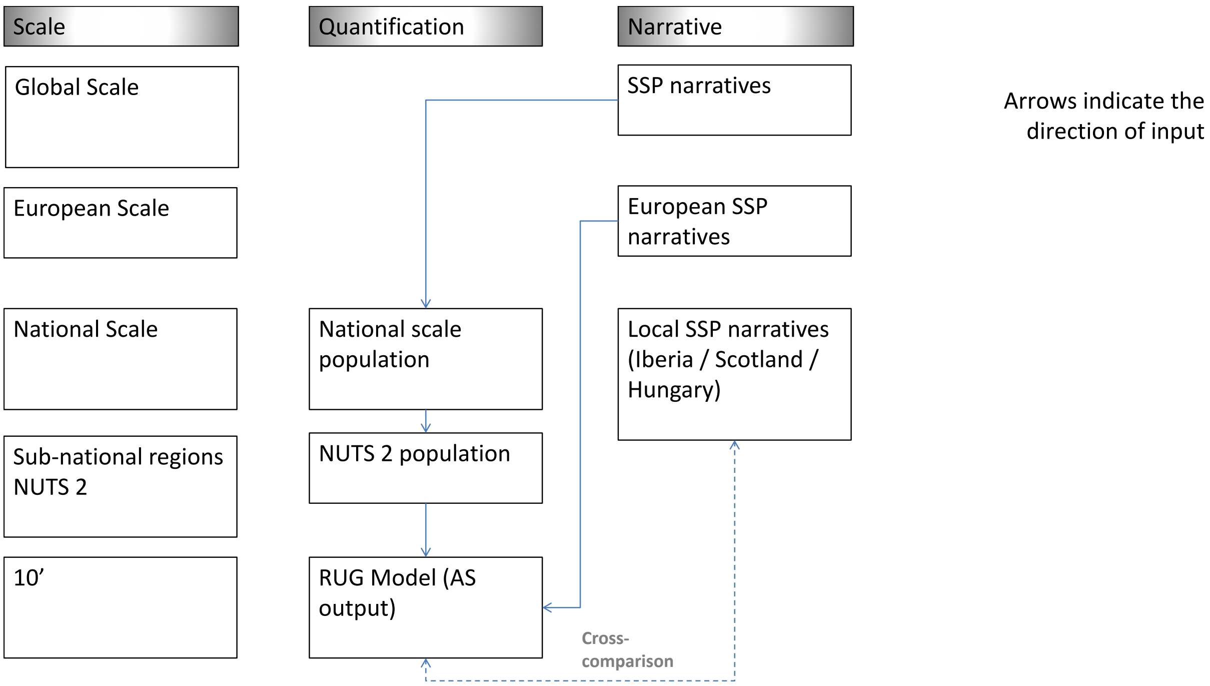

Figure 3.1: Conceptualisation of methodology. Arrows indicate direction of input

that joined the EU prior to 2004 (EU-15), "New EU member states that joined as of 2004 with high income" (EU-12H) and "New EU member states that joined as of 2004 with medium income" (EU-12M) (see "Aggregation on the 32 region level" in the SSP database: https://tntcat.iiasa.ac.at/SspDb/. This division is shown in Figure 3.3). Croatia was part of the "Eastern Europe (excl. former Soviet Union and EU member states)" aggregation group. However, its data was added to the list as part of the pan-European modelling. Its modelled trends followed the same patterns as the new EU member states that joined as of 2004 with medium income. The crucial elements that maintain consistency across quantifications and narratives, global SSP narratives contextualise the national scale quantifications and the European SSPs contextualise key scenario model variables. The consistency between global and European SSPs is ensured by applying equivalent narratives, i.e. fully matched SSPs across scales (Kok et al., 2018). The link across the multi-scale European SSP narratives is explained in detail in the next session.

3.2.1 Multi-scale European SSPs

Within this analysis, population-centric change, consisting of demographic trends and societal preferences (Terama et al., 2017b), is one of the most significant driver in urban land use development across scenarios (Terama et al., 2017a). Demographic trends are used as an input to the Regional Urbanisation Growth model (RUG). Demographic drivers within the RUG model are (1) consistent with the global trends of population and spatial planning quantified at national scale (Jiang & O'Neill, 2017; Kc & Lutz, 2017), and (2) influenced by the European SSP narratives (see Figure 5.3). These European SSP narratives were enriched with context-specific 'urbanisation narratives', describing artificial surface expansion driven by changes in total population, population structure, societal preferences and spatial planning. The direction of these drivers is summarised in the urbanisation narratives of the European SSPs. European SSP narratives were developed in a participatory way with experts from multiple disciplines and countries taking part in the process (Kok et al., 2018; Pedde et al., 2018c). The global SSPs (O'Neill et al., 2017) are the starting point for developing the European SSPs (Kok et al., 2018) by downscaling the global narrative to a Europe-wide narrative. Whilst downscaling a narrative is often the step for developing downscaled quantitative scenarios (van Vuuren et al., 2010), the methodological limitations of 'translating' the narratives (from global to local and from qualitative to quantitative scenarios) have been addressed by the European SSPs by maintaining the same assumptions and similar macro trends in both the global the European SSPs (Kok et al., 2018), reducing expert judgement assumptions in the direction of trends and, in some cases, key quantifications (Pedde et al., 2018c). In terms of demographic change, for example, both global and European SSPs assume high population growth in SSP5, stabilising trends in SSP1 and a total population decline in both SSP4 and SSP3. Overall socio-economic development is also identical in the global and European SSPs, with SSP5 being the fastest growing economic scenario (although not environmentally sustainable), SSP1 the most sustainable both economically and environmentally, SSP4 counting for moderate economic growth but with high disparities within and across countries, and SSP3 resulting in socio-economic decline and inequalities. The leading narrative, following the logic of global SSPs, was combined with an existing European socio-economic scenario framework (Harrison et al., 2013, 2015). Additional, local European versions of the SSPs were also developed (hereafter 'local SSPs') for Scotland, Iberia and Hungary, with stakeholders selecting the main assumptions in a facilitated process that allowed for defining the future challenges to mitigation and adaptation (Gramberger et al., 2015). In terms of drivers, the local SSPs are generally consistent with the European SSPs but their relevance may differ if stakeholders consider scale relevant processes to result in diverging trends. The choice of the location for the local case studies is independent of RUG model constrains and local SSPs and RUG model are therefore unrelated in Figure 5.3. This choice, and the large socio-economic differences across the case studies, imply that the local SSPs are developed with a 'bottom-up' approach, unconstrained by RUG parameterisation. RUG, instead, is designed as a coherent 'top-down' modelling approach, from global and European scales (Figure 5.3). This analysis is therefore at the intersection between RUG model output and the local SSPs narratives: we focus on identifying qualitative information from the local and European SSP narratives on population, mobility and urbanisation trends to discuss similarities and differences with key driving forces and their relevance for European scale urbanisation modelling. The scenario narratives are published in Kok et al. (2018) for Europe, in Li et al. (2017) for the Hungarian case study, in Dunn et al. (2017) for Scotland

and in Tàbara et al. (2018) for Iberia. An overview of the case studies and sectors for decision-making is reported in Lourenço et al. (2018) and the summaries of all the local SSPs is provided in the IMPRESSIONS deliverable (Kok & Pedde, 2016).

3.2.2 Integrating SSP narratives and life-cycle assessment in spatially explicit urbanisation modelling

The Regional Urbanisation Growth (RUG) model is documented in Terama et al. (2017a) and Terama et al. (2017b). The focus for this paper is the influence of global scale SSP narratives and European SSP parameterisation, more precisely the links between the total population, age and life-cycle stage, residential preferences and planning (Terama et al., 2017b) on modelling outcomes. The RUG model develops time-dependent artificial surfaces, differentiating between multiple residential (defined as a function of population/building density) and non-residential areas in each unit (NUTS-2 geographical scale). The area of each residential type is calculated as a function of the total population, consistent with the global SSP narratives (Figure 5.3), and regionally/scenario defined residential preferences, that is, the 'attractiveness' of residing in each residential type. Non-residential expansion is a function of the predicted change in residential areas and a 'rate of industrial development'; a function of economic/manufacturing development within the socio-economic scenario. The types of artificial surfaces are spatially autocorrelated with the residential transition matrix, which defines the likelihood of each artificial surface type being observed in the presence of the artificial surface type being considered. Non-residential and residential surfaces are driven by the autocorrelation factor and scenario-specific industrial development and residential preference parameterisation (Terama et al., 2017a). Fundamental to the residential preference parameterisation in RUG is the concept that life-cycle stage influences the residential preferences of individuals/households. To this end, RUG further distributes the population of each region across a set of preferred residential types in a 10' grid. Preferences can represent a choice driven by an attraction for a given residential type, or an enforced residential selection which is required (by the population) to satisfy a need (for jobs or access to social services). Preferred residential types are defined as a function of age-group, the scenario being considered, and a baseline (region specific) description of the population's residential preferences. The RUG baseline (year 2010) population structure at a regional (NUTS-2) scale was derived from Eurostat (2015). Demographics were modelled at the resolution of six age-groups: (i) 0 – 14 years, (ii) 15 – 29 years, (iii) 30 – 49 years, (iv) 50 – 64 years, (v) 65 – 74 years, and (vi) greater than 75 years, defined to represent distinct life-cycle stages and ensure alignment with important life-cycle events, such as retirement (Carter et al., 2016). Populations within the same age-group were assigned the same properties and residential preferences, with additional consideration made for dependent children (Terama et al., 2017b). Although the European SSP storylines were the key in defining future residential preferences, which reflect changes in spatial planning and societal attitudes, the ‘global demographic’ SSP database (Wittgenstein-Centre, 2015) provided the national scale population at each future time-step.

3.2.3 Analysis of correlations

To analyse the relation between artificial surface trends and its drivers, we carried out a correlation analysis (R^2) of selected RUG drivers against the artificial surface output. The drivers were selected to represent the different scales modelled in RUG: 1. Total population (PO) based on assumptions developed in the global narratives 2. Elderly (>65 year old population) (AG), consisting of the combination of age group (AG5) and (AG6) populations (see Figure 3.4) 3. Fertility (FE), to represent the different classifications of population trends based on current fertility rates These variables also approximate the three scales which influence RUG as mentioned in the method (Figure 3.1 and section 3.2.2): total population trends relate to the global SSP trends (Kc & Lutz, 2017; O’Neill et al., 2017), ageing relates to the European scaling approximating lifestyle and preferences (Carter et al., 2016; Terama et al., 2017b) and fertility relates to the national scale assumptions which divides countries in low and high fertility countries (Wittgenstein Centre, 2015). In summary, RUG is influenced by assumptions at global scale through the global SSP quantification of total population growth, at the European scale through the parameterisation of European narrative preferences connected to socio-economic factors, such as poverty, lifestyles and at national scale with assumptions on fertility and migration. Coherence across these assumptions was tested firstly by analysing the European broad-scale modelled results and by measuring the sensitivity of the multi-scale assumptions (population, preferred residential type as a function of age and fertility) against the modelled results (Section 3.3.1) and secondly by analysing these trends against local scale narratives (Section 3.3.2).

3.3 Results

3.3.1 Broad-scale artificial surface change for Europe and selected European countries

At the European scale, the greatest artificial surface expansion (AS) is observed in SSP5 with an increased 150% AS compared to current artificial surface of about 16.7 million ha. This development could be classified as urban sprawl (Terama et al. 2017), and is a clear characteristic of the SSP5 socio-economic scenario assumption in which a growing, individualistic society with increasing wealth seek the larger properties and lower population densities associated with suburban, town and rural areas. In this scenario, market logic prevails, driving urbanisation as the most preferable and profitable pathway for development. The artificial surface demands of an expanding population are further magnified by a shift towards expansive residential types. Contrasting the urban sprawl of SSP5 are those socio-economic scenarios that promote migration to, and densification of, cities. Both SSP1 and SSP4 are characterised by limited artificial surface increases by 2100 with, compared to the baseline, 10% increase for SSP1 and 5% increase for SSP4 (Figure 3.2). However, the mechanisms/drivers of this change differ significantly between the scenarios. Within SSP1 an increasingly environmentally aware society values sustainable urban development and a shift towards more compact, high density living; a shift that mitigates substantive artificial surface expansion. Urban centres within this socio-economic scenario are vibrant, attractive, environmentally-friendly residential areas. These vibrant, attractive urban centres are in stark contrast to the urban ghettos predicted for SSP4. Within this socio-economic scenario, urban living is driven not by societal preferences, but in response to a poorer society moving to urban centres in search of jobs and social services. This urbanisation combined with a declining population limits artificial surface expansion within this socio-economic scenario even more than the SSP1 scenario. The intermediate artificial surface expansion of SSP3 is driven by urban migration and countryside abandonment. In contrast to the 'urban ghettos' of SSP4, however, urbanisation in SSP3 is focused on suburban (peri-urban) areas, i.e. regions that have a larger artificial surface 'footprint' than more densely populated city centres. As a consequence, more artificial surface sprawl occurs in this scenario. This sprawl is further magnified by weak planning legislation, which leads to uncontrolled development. The SSP trends for Europe have a similar direction of change in the countries selected for case study (Figure 3.2), i.e. Spain and Portugal (Iberia), Hungary, Scotland. Trends for Bulgaria are also shown, to represent one of the low-fertility countries of (Figure 3.3). Overall, the AS increase tends to be highest in the UK and Spain trends, i.e. always above the European average except for Spain in SSP3. Trends for Portugal tend to be closest to the European average. Hungary and Bulgaria have the lowest AS growth with increase in AS between 0% and 1%. The exceptions are (1) a 13% AS increase in 2100 in the SSP3 scenario for Bulgaria, which is the only country reversing population decrease by 2100 (Figure 3.4), and (2) 61% AS increase in 2100 in the SSP5 scenario for Hungary consistent with population growth, albeit at much slower pace than UK, Spain and Portugal.

The broad-scale European trends, as outlined above, follow the predicted socio-economic response (and storyline) of each SSP but show variability across countries. When mapped at the detailed model resolution (10' cells) increased spatial variability in the patterns of artificial surface change become evident (Figure 3.3). Across socio-economic scenarios, a clear distinction exists in the modelling outcomes of the group of European countries part of the EU-12M region of the SSP IIASA database (Bulgaria, Croatia, Latvia, Lithuania, Malta, Romania) and the rest of Europe; a distinction which can be ultimately linked to

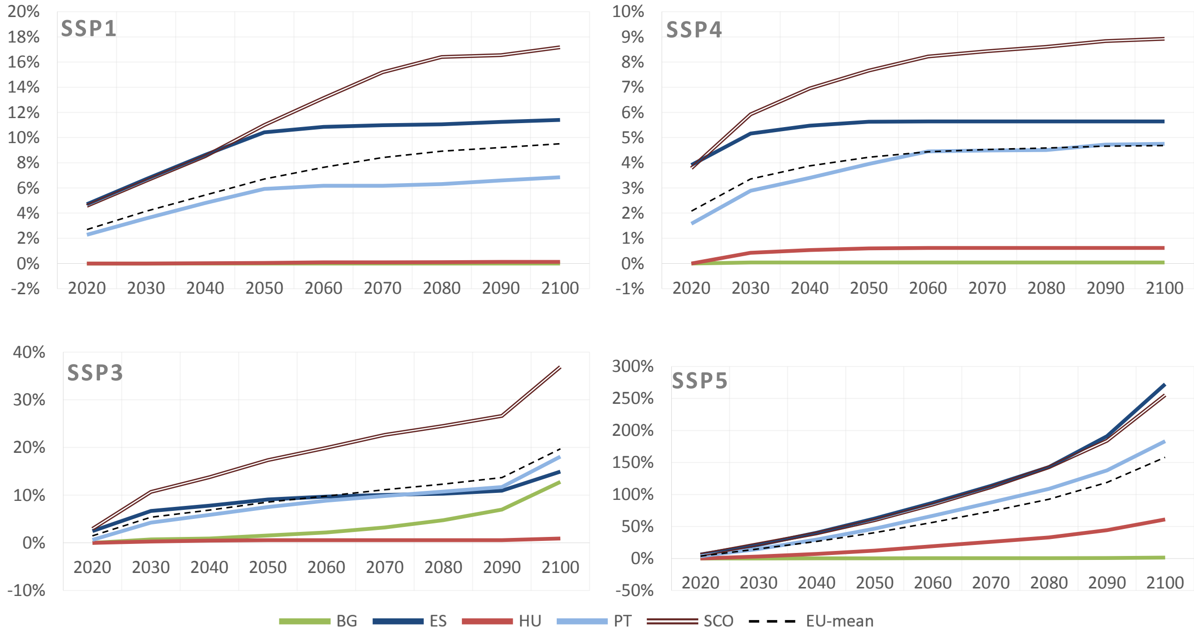

Figure 3.2: Projections of artificial surface development for four Shared Socio-economic Pathways (SSPs) aggregated at country scale in Bulgaria, Spain, Hungary, Portugal, and Scotland. The y-axis shows % change of artificial surface compared to baseline and the x-axis decadal time steps from 2020 to 2100

the (globally) predicted demographic and population changes in each scenario.

Population change estimates for this group of countries (Wittgenstein Centre, 2015), do not predict the significant increases in population associated with SSP5 in the remainder of Europe (Figure 3.4). Instead, the countries are, within SSP5, characterised by an ageing, but overall decreasing population. As a consequence of this declining population, model outcomes predict that the population could be housed within the existing artificial surface footprint (although the housing stock may change) limiting artificial surface expansion and urban sprawl (Terama et al., 2017b). In contrast to the remainder of Europe, within the subset of countries, the highest artificial surface change (and urban sprawl) is associated with SSP3. While SSP3 is also characterised by an ageing and declining overall population, the slower rate of change combined with a shift towards suburban development (associated with urban migration and weak planning laws) results in artificial surface expansion. In this context it is evident that a declining overall population is insufficient to prevent artificial surface expansion if changing demographics and/or residential preferences result in a shift to more expansive residential types. The rest of Europe more closely follows the broad trends with the most substantive artificial surface expansion occurring in SSP5.

The SSPs highlight the potential extent of future artificial surface change under very

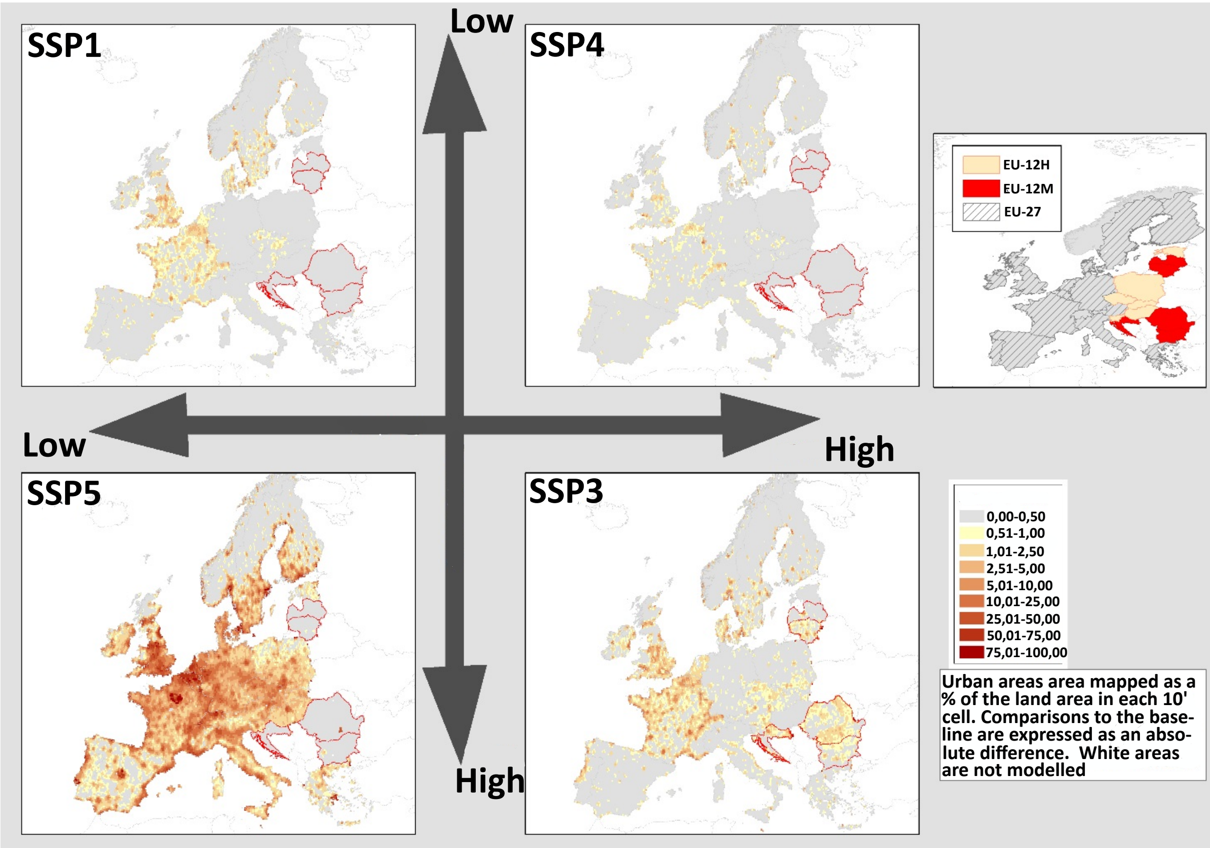

Figure 3.3: Map of the predicted change, from baseline 2010, in artificial surface extent (as a percentage of the 10' cell land area) by 2100 under four different socio-economic scenarios, highlighting trends for European low-fertility countries (perimeters in red). Vertical axis is 'carbon intensity' and the horizontal axis is 'inequality'

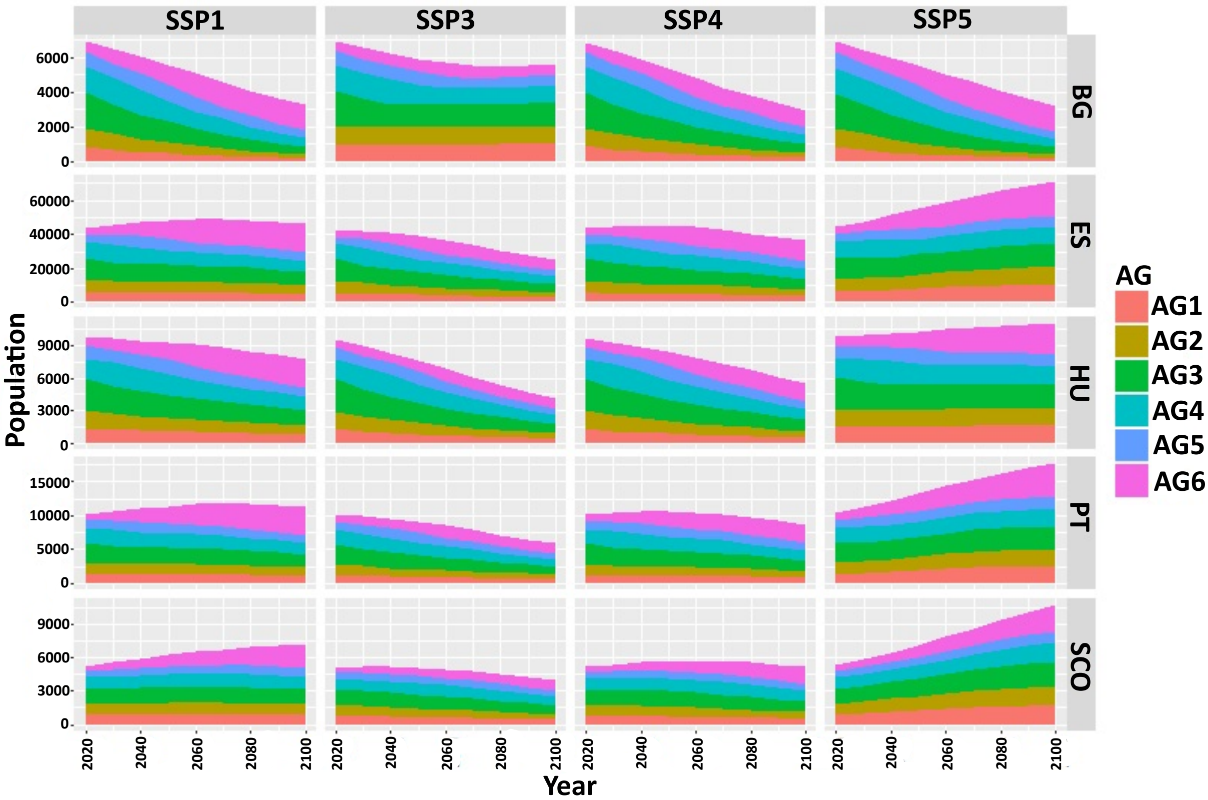

Figure 3.4: Projections of total population in Bulgaria, Spain, Hungary, Portugal, and United Kingdom, identifying structure at a regional (NUTS-2) scale, was derived from Eurostat (2015). Demographics were modelled at the resolution of six age-groups: (AG1) 0 – 14 years, (AG2) 15 – 29 years, (AG3) 30 – 49 years, (AG4) 50 – 64 years, (AG5) 65 – 74 years, and (AG6) greater than 75 years

different socio-economic scenarios. Important distinctions between the scenarios include (i) the potential to mitigate artificial surface expansion via increasing population and population densities (as evident in SSP1), (ii) the potential of artificial surfaces to 'sprawl' in the presence of increasing populations, and/or changing residential preferences, and (iii) the regional variability in artificial surface expansion. In Figure 5, three input variables are correlated against the artificial surface results as explained in the method (section 2.3). The variables are [AG], i.e. population >65 year old (AG5 and AG6 groups from Figure 3.4); [PO] i.e. total population, and [FE] i.e. fertility. The analysis of the model variables based on the R^2 value shows the relative importance of each of the population variables that we considered with respect to the development of artificial surfaces. It also shows which variables had very little influences in determining artificial surfaces in different countries (Figure 3.5). The low R^2 value shows little correlation, but a strong negative R^2 has little correlation but it still important in determining the results. For example, a 0.77 R^2 value (or higher) between FE and AF, denotes a high correlation between fertility and artificial surface for Portugal, Spain and Hungary. A value of 0.08 between population and artificial surface trends in Bulgaria means there's no correlation. In all scenarios, a correlation of >0.50 is observed between all variables in all selected countries, with the exception of [AG] and [PO] variables for Bulgaria. This suggests that, for this country, fertility trends better relate to artificial surface than ageing or population growth. That means that the choice, made at global scale, of placing Bulgaria in a different category from the other countries of this selection (see also different population trends for Bulgaria, compared to the other countries in Figure 3.4) has 'overwritten' the RUG modelling assumptions of assigning residential preferences to the same age-group. This is true at least for Bulgaria and the other countries in the same categories (which had similar R^2 trends).

The correlation analysis further shows that fertility in Bulgaria is also strongly uncorrelated to total population growth and, especially, aging. For Spain and Portugal (Iberia), Scotland and Hungary the correlation is always positive and >0.50 except for a low correlation (0.36) between fertility and ageing in Scotland. The analysis suggest that spatial variability should be interpreted carefully to understand what assumptions are reflected in the results. In the case of the same SSP narrative, artificial surface trends reflect fertility assumptions developed at global scale for each country (in low fertility countries, such as Bulgaria) and scenario assumptions on population growth (global and national scale) and ageing (European and NUTS2 scale), especially when the two trends follow a similar growth path.

3.3.2 Multi-scale analysis of urbanisation in SSP narratives

Assumptions on spatial development and population growth, within European scale modelling, directly influence pan-European modelling outcomes. For this reason, we

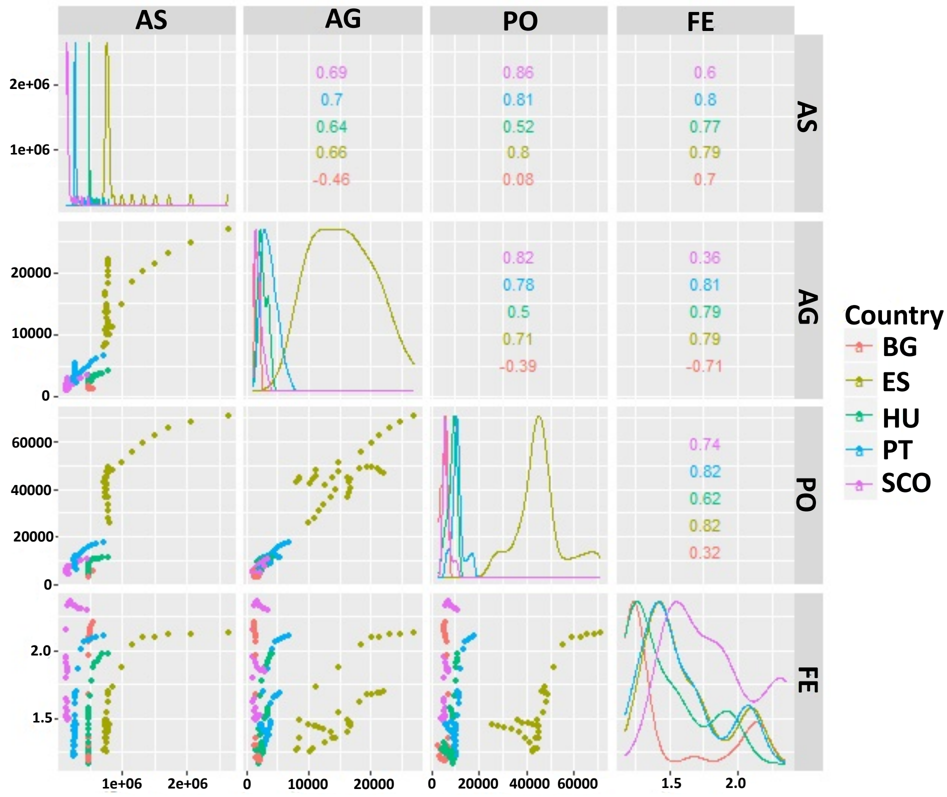

Figure 3.5: Correlation key between national scale model input of artificial surfaces (AG=population in age group 5 and 6, i.e. >65 year old; PO=total population and FE=fertility rate) and output (AS= artificial surface). N=72 for each distribution.

propose the integration of local SSP narratives in the assumptions, in particular the key trends of urbanisation and assumptions of population growth (with a special focus on migration, see Table 3.1) to analyse divergences and similarities at local (Iberian, Hungarian and Scottish) and European scales.

SSP1: Sustainability

In SSP1, the global and European assumptions on urbanisation reflect a fast urbanisation process as a result of high income growth (Jiang and O'Neill, 2017). The European SSPs, however, further specify that the shift towards compact cities is tempered by a preference for green space. In the Iberian case study people move from cities to rural areas, preferring small towns to cities and contributing to the "repopulation of the countryside", suggesting that stakeholders did not consider living in small settings to be inconsistent with a sustainable lifestyle. A similar interpretation, but more directed at correcting current trends of depopulation of the countryside, has been provided by the Scottish and Hungarian stakeholders. More specifically, in Scotland, the countryside is the destination of incoming migrants to "reinvigorate communities" and, in Hungary, small towns become an attractive alternative to "overpopulated" Budapest. The migration trends are consistent across scales (global – European – local), with the exception of Scotland: the "medium" trend of the global SSP1 is the result of "low immigration and limited movements in Europe" and a balanced migration in Iberia (explicitly accounting for lower emigration). In Scotland, instead, returning emigrants and foreign migrants result in strong migration flows.

SSP3: Regional Rivalry

In SSP3, the global assumptions reflect a slow urbanisation process as a result of low income growth, limited mobility and poor urban planning (Jiang and O'Neill, 2017). This does not mean that cities will not grow in Europe: cities will grow at the fringes, because of sprawl, due to the lack of economic opportunity and consequent countryside abandonment. This development is usually not favoured in sustainability-centric assessments that aim at compact cities (see SSP descriptions in e.g. O'Neill et al. (2017)). In the Iberian case, cities are assumed to grow as a result of low employment and countryside depopulation. In the Hungarian case study, low employment and poor urban planning result in the opposite trend, i.e. people's movement to the countryside and the urban fringe from larger cities. Migration is not a straightforward driver: globally, low migration is assumed; in Europe as a whole people will emigrate; in the local case studies migration trends are heterogeneous: high immigration from Africa and emigration from Iberia, low migration to and from Scotland, and high immigration is assumed to Hungary.

SSP4: Inequality

In SSP4 the global assumption is that income inequality between rural and urban regions acts as as pull factor towards urbanisation, although ageing is assumed to be a limiting factor in the rural to urban mobility. Similarly, in the European SSP4 densely populated cities attract more and more dwellers resulting in the creation of urban ghettos. This trend is consistent with the Hungarian and Scottish case studies. In Scotland "the unemployed and new immigrants are forced to move to overcrowded housing surrounding the cities and main towns" and in Hungary there‘s a continuous movement from rural areas to cities. As in SSP3, migration trends vary greatly across regions in SSP4. In Iberia and Hungary a strong European Union is assumed to effectively control immigration. However, a wave of immigration affects Scotland throughout the scenario. Overall, the European narrative assumes controlled migration but introduced also the flows of illegal immigrants (which is not accounted for in the modelling exercise).

SSP5: Fossil-fuelled Development

In SSP5 the mobility trend is high but does not necessarily correlate with compact urban development, but quite the opposite. The scenario is characterised at the European scale by affluence driven sprawl and strong preferences for pristine surroundings. In this scenario the demand for new artificial surfaces is by far the highest. In the case studies, within Iberia, movement to cities is strong following job opportunities in corporations. At later time points, some major cities such as Madrid, are gradually abandoned as people migrate towards the coast. For the Scottish case study, most people are expected to be living in urban areas. In terms of migration, the scenario also depicts large numbers. This is in line with the overall population development which is one of strongest growth. At the European level, migration is assumed to be mostly towards Europe from less strong economies. Also in the case studies, migration from Africa is expected to Iberia and the rest of Europe. Retired, rich northerners will also move to Iberia. By the end of the century, however, a collapse of the existing development model leads to emigration from Iberia towards Northern Europe. Mobility is expected to be high for professionals across Europe (See Table 3.1).

By 2100, artificial surfaces within all scenarios, still constitute less than 10% of the European land area. However, the magnitude and spatial distribution of this change has the potential to (i) increase the competition for land (for example, for food production or nature protection) with potential tensions between land use owners/interest groups, and (ii) detrimentally impact ecosystem services and biodiversity both within urban areas and in neighbouring regions. Impacts would affect not only the extent of natural areas but their quality given the market rather than ecological focus of society in this scenario (see also (Güneralp & Seto, 2013) . The insights from the cross-scale comparison suggest potential competition for land in a sustainable scenario (SSP1) and the effect of detrimental impacts in business as usual scenario (SSP5). In all local case studies, SSP1 added the dimension of current depopulation trends in the countryside throughout Europe, leading stakeholders to emphasize less the characteristics of compact cities as simulated for global and European trends, and focus instead on environmentally-

Table 3.1: Summary of SSP trends of urbanisation (including mobility within countries) and migration (including emigration and immigration across countries). Global trends for urbanisation are derived from Jiang and O'Neill (2017b) and migration from (KC and Lutz, 2016), EU28 trends from Terama et al. (2017b), and local case studies from the IMPRESSIONS scenarios (Kok et al., 2018)

Scenario	**Spatial scale**	**Urbanisation**	**Migration**
SSP1	Global	Fast urbanisation	Medium
	Europe	Increasing (compactness)	Low immigration
	Iberia	Small towns and repopulation of the countryside	balanced migration
	Scotland	High and repopulation of the countryside	High immigration and expats return (total population increases)
	Hungary	Aging, reversed depopulation, high life-expectancy, stability	Balanced migration (first high immigration). Emigration declines
SSP3	Global	Slow urbanisation	"Limited mobility across regions"
	Europe	Decreasing, sprawl, low mobility	Emigration
	Iberia	Country(side) depopulation, ageing	High immigration from Africa, increasing emigration from Iberia
	Scotland	NA	Immigration remains but overall population slightly decline (fertility)
	Hungary	people move to the countryside and the urban fringe from larger citie ("urban and rural ghettoes")	steady and massive influx and settlement of migrants and refugees
SSP4	Global	Central and fast urbanisation	Medium
	Europe	Increasing (compactness) high mobility is high for the elite	Selected immigration and illegal migrants
	Iberia	NA	High immigration from Africa, until stabilisation in 2040s
	Scotland	First, elderly move to retire in Scotland, as economy worsens the unemployed and immigrants move to urban ghettoes	Increased migration
	Hungary	Rural to urban migration	EU-controlled stable migration flux
SSP5	Global	Fast urbanisation	High
	Europe	Sprawl and high mobility	High immigration from poorer countries
	Iberia	First, mobility to cities. From 2040s abandonments of large cities	Migration from Africa and elderly (retirement) from Northern Europe. From 2070s, mass emigration to Northern Europe
	Scotland	High urbanisation	High immigration
	Hungary	Urbanisation and mobility, but diseases decimate the population	Emigration (brain-drain) decreases

friendly living arrangements in the countryside. In such scenarios, further assumptions on preference for locally produced organic food and decreased food imports may result in competition with land-use for nature conservation. Likewise, SSP5 added the dimension of resource overexploitation, leading Iberian and Hungarian stakeholders to account for the negative effects of business as usual such as population decimation (Hungary) and city abandonment (Iberia). These trends are in stark contrasts to global and European trends of unrestricted economic, population and urbanisation growth until 2100. The socially unequal scenarios, SSP3 and in SSP4, added the dimension of high migratory fluxes across Europe and to Europe, especially in the Iberian and Hungarian narratives. These migratory trends are not reflected in the pan-European modelling which focuses on assumptions of mobility and preferences as function of income. These assumptions from local stakeholders may be at odds with projected trends of artificial surface, especially for the very slow artificial surface increase in Hungary in SSP3 (cf. Figure 3.2).

3.4 Discussion

The comparison of the subset of European countries has highlighted the influence of differing population trajectories stemming from the global SSP assumptions and national population projections, on artificial surface development. However, by exploring the results it is evident that there is a complex interaction of population structure, societal preferences and spatial planning as influenced by life-cycle and population growth. These same factors have the potential to both restrict (SSP1) or magnify (SSP5) the expansion of artificial surface. Furthermore, a declining population does not guarantee static artificial surface footprints as changing residential habits will also drive urban expansion as observed for the subset of European countries in SSP3. Also, changes in population may lead to effects on poverty and isolation of rural populations, and negative effects overall economy and health, which in turn further affect artificial surface expansion (Linard et al., 2012). The Hungarian SSP3 narrative, for example, reflected these complex relations, with fluctuating population patterns and health effects in the Hungarian SSP3 (Li et al., 2017). The results also show that urbanisation trends might be misinterpreted, if scenario users and other modellers are not aware of the full spectrum of uncertainties/assumptions and their accumulation/interaction across scales. Especially when we compare the scenario assumptions made at European scale with local scale scenarios, we highlight the importance of common and diverging assumptions due to specific importance to local case studies. This analysis further strengthen the importance of understanding what assumptions are behind European scale trends and how they should be interpreted to be relevant to both European and local policy making. Our approach combines the advantage of both qualitative and quantitative forms of analysis, with narratives to develop consistent assumptions when quantifications cannot be included in the analysis. The quantified scenarios add a dimension of replicability and a more systematic comparison across scales which helps to identify inconsistencies. Although the method to link between narratives and quantified scenarios is similar to that used in global scenario exercises (O'Neill et al., 2016; O'Neill et al., 2017), this link is not fully transparent (Pedde et al., 2018c). A systematic approach to link qualitative elements in multi-scale scenarios exist to develop consistent scenario (Schweizer and Kurniawan, 2016). In this study, however, we treated the question of multi-scale scenario consistency as normative and fully stakeholder-driven. In other words, the stakeholders decided what socio-economic trends were relevant for their case study and the direction of their scenario– including u-turns and non-linear developments – within the SSP worlds. Even though the European SSP narratives are internally consistent, in line with the global SSP narratives, the global-European-regional quantitatively downscaled results do not automatically translate to locally specific trends. Countries have different fertility rates and regional population structures. However, these differences were not flagged in the European SSP narrative. National fertility assumptions are not consistent, nor inconsistent with the European or global SSP narratives. By picking up the global data and narratives and applying them in AS modelling, their assumptions are inherent in our outcomes. In this case, the weight of differences between fertility assumptions between different country groups was visible for the artificial surface development, particularly in SSP5. As a consequence, spatially explicit analyses, such as this one, entail a trade-off: either undertaking (a) a computationally expensive calibration with local scale data and precise local assumptions which however reduce comparability across regions, or (b) an analysis based on more generic assumptions which may hide locally biased patterns but which produces spatially explicit and comparable outcomes. Both options have intrinsic value, addressing different stakeholders and policy fora. The results of this analysis aim to inform decision making at the EU scale. They are based on set of EU and global scale assumptions, they are not country-specific to the extent that all local information would be validated with stakeholders. Decision-makers need to be informed and act in the context of the wider set of assumptions being propagated across scales. While it is possible to downscale both SSPs and global scale trends (as we do with the population data), which is advantageous in terms of modelling outcomes, it is not possible to separate these downscaled approaches from their overriding assumptions: uncertainties and assumptions will be inherited in the results and must be analysed together with the results. Our approach allows to take advantage of a European scale modelling approach, while analysing the underlying assumptions and interpreting them also in light of locally derived drivers and assumptions.

3.5 Conclusions

European artificial surface future trends reflect scenario parameterisation at multiple scales, but the fertility assumptions, developed at global scale for each country, are reflected unevenly across scenarios and countries. Other factors, highlighted by stakeholder-developed narratives at sub-global scales, can also influence the interpretation of the trends. For example, local narratives highlighted migration as a key driver for population changes, rather than fertility and mortality as emphasised in global population modelling. Preferences for urban or green spaces were consistent across scales, although the local narratives added nuances on the link between urbanisation and rural dwelling. To ensure the correct interpretation of modelling results, all drivers and assumptions need to be communicated along with key uncertainties. While valuable for consistency across regions and scenarios, global SSP scenarios (Riahi et al., 2017) and further application of global databases at sub-global scale, should be adapted to align and interpret quantitative downscaled data with bottom-up data, even when if this comes in qualitative form, to better capture the complexity of socio-economic drivers at multiple scales.

Chapter 4

Archetyping Shared Socio-economic Pathways across scales: an application to Central Asia and European case studies

This chapter is based on:
Pedde, S., Kok, K., Hölscher, K, Oberlack, C., Harrison, P.A., Leemans, R. (2018). Archetyping Shared Socio-economic Pathways across scales: an application to Central Asia and European case studies. *Under review in Ecology & Society*

Abstract

Complex interactions between climate and socio-ecological drivers and impacts has resulted in the rise of multi-scale scenario analysis. Although linkages across scales and levels depends on process and objectives of the specific problem, global-regional-local multi-scale scenarios often involve downscaling global scenarios with links to locally developed scenarios, posing a question on what 'consistency' across scales means in multi-scale scenarios. The methodology consists of two steps. First, we analyse the Shared Socio-economic Pathways (SSPs) narratives against four scenario archetypes. Second, we utilise Cultural Theory to classify trends of recurrent scenario drivers (Socio-economic, Technology, Environment, Economy, Policy = STEEP) to compare divergences in SSP narratives in multi-scale case studies. The results show that the global narratives have homogeneous worldviews and the match with the four archetypes is strong for three scenarios. Although similarities to the global narratives appeared in all sub-global narratives, in terms of dominant worldviews, the complexity and richness of sub-global SSP narratives show that different worldviews coexist in the same narratives,even in the well-established utopia-dystopia scenarios. For example, the multiple interpretations of 'sustainable development' were visible through different beliefs in governmental regulation. Also, the "business as usual" SSP5 narrative was highly dependent on the interpretation of how individualism affects society and the environment across the case studies, making SSP5 the most diverging narrative at sub-global scale. Because of these nuances, multi-scale scenarios entailing narratives and participatory scenarios development should better integrate bottom-up knowledge in the process of downscaling STEEP drivers.

4.1 Introduction

A key aspect to understanding the potential consequences of high-end climate-change impacts is the exploration of uncertainty in long-term alternative socio-economic futures, also in the form of scenarios (Field et al., 2014). The complex interactions of climate-change impacts and drivers across scales has led to the development of multi-scale scenarios (Biggs et al., 2007; Kok et al., 2007). However, scenarios at sub-global scales are frequently inconsistent with global scenarios, limiting coherence in the use of multi-scale scenarios (Pedde et al., 2018a; de Ruiter et al., 2017). This paper utilizes scenario archetypes and Cultural Theory to demonstrate how the archetyping of the global Shared Socio-economic Pathways along their worldviews supports coherence in multi-scale scenario development.

Multiscale analysis has evolved from its early system theory conceptualisation developed in the 1980s in the ecology hierarchy theory by Allen and colleagues (Allen & Starr, 1982; Allen & Hoekstra, 1992). According to this theory, components of complex systems are organized hierarchically based on multiple spatio-temporal and functional scales. Linkages within socio-economic, political and biogeochemical systems (Gallopín et al., 2001; Gibson et al., 2000) or, in other words, linkages in spatial, temporal scales (or 'dimensions' as in Vervoort et al. (2012) and levels (positions on a scale) of these systems (Cash et al., 2006; Gibson et al., 2000) have also evolved in scenario exercises. A degree of interconnectedness, such as in multi-scale scenarios, is desirable because the consistency between global and regional level is paramount to assess impacts and vulnerabilities (Zurek & Henrichs, 2007). However, different degrees of interconnectedness are possible, from fully equivalent scenarios at different scales to loosely linked scenarios, depending on their desired outcome and purpose (Biggs et al., 2007; Zurek & Henrichs, 2007). More precisely, the degree of interconnectedness depends on the the direction that key variables normally take (such as GDP and population) and define also whether multi-scale scenarios are consistent with each other. Multi-scale scenarios tend to include stakeholders engagement to better understand impacts due to socio-economic, political and natural (e.g., climate and ecological) processes at different scales (Biggs et al., 2007; Kok et al., 2007). The practice of multi-scale scenario development has involved downscaling global scenarios, to define a suitable scale for impacts and vulnerability assessments. However, the sub-global scenario scale scenarios often do not match the global narratives because the scenarios elements, such as storylines, assumptions, and model quantifications, were not developed to explore variation of factors relevant to impacts and vulnerability assessments (van Ruijven et al., 2014). The new global Shared Socio-economic Pathways (SSPs) have been developed with the aim to providing socio-economic pathways of key socio-economic drivers along the dimensions of challenges to mitigation and to adaptation which are scalable to different regional contexts (Kriegler et al., 2012). The global SSPs have been designed as 'pathways' exploring the relevant uncertainty space of challenges to mitigation and adaptation to climate change (O'Neill et al., 2015, 2017). The design of the SSP global storylines is suitable for the development of consistent cross-scale global and sub-global socio-economic storylines (Ebi et al., 2014; O'Neill et al., 2015) because of the inclusion of indicators at global scale relevant to sub-global analyses therefore providing a global context to local future scenarios (van Ruijven et al., 2014).

Recent examples of the application of global SSPs include sub-national and sub-sectoral SSP storylines extensions for the South-east USA (Absar & Preston, 2015) and the extension for Latin America within the Robin project (Jones & Kok, 2014) and more recently Kebede et al. (2018). These extensions differ in sectoral and geographic extension, but are methodologically similar in that they both develop sub-global storylines which are 'nested' in the global SSPs. One challenge with 'nesting' global scenario is that sectoral, spatial and temporal extensions still incorporate subjective elements in defining what is 'consistent' across scales. Because scenarios consist of both model output and narratives, 'consistency' can be defined with reductionist methods, i.e. by reducing narratives to single variable trends, generally belonging to five categories, so called 'STEEP': society, technology, economy, environment, policy (Hunt et al., 2012). However, 'consistency' can also be defined holistically by analysing the richer context of the narratives, which contains further linkages and complexity that are not captured by model variables (Rasmussen, 2005). Because the dominant approach to assess consistency in multi-scale scenarios is the reductionist approach, the meaning of what 'consistent scenarios' actually means is only partly explored. One method for exploring consistent narratives and variables is the identification of commonalities in global scale scenarios and grouping them in scenario families (van Vuuren et al., 2012a) or archetypes (Hunt et al., 2012). These studies conclude that scenarios share common elements, i.e.similar assumptions on the trends of key variables. Although their analysis focuses on the global scale, the utilisation of these scenarios by regional/local scientific community urges: (1) a clarification on the concepts of scenario families and archetypes, considering that these terms have been used interchangeably and (2) a re-consideration of the meaning of scenario 'consistency' across scales, once sub-global scenarios are developed to be 'consistent' within their global scenario counterpart. In this study, we analyse the consistency of multi-scale SSP scenario narratives to identify how scenarios vary within the same type of scenario and discuss the importance of diverging assumptions in multi-scale scenario approaches. The methodology builds on two existing approaches to analyse scenario archetypes. Firstly the qualitative scenario mapping of global SSPs onto existing scenario archetypes, to test whether SSPs can be categorised within existing scenario archetypes. Secondly, the global and a selection of sub-global SSPs are analysed using Cultural Theory to systematically compare similarities and divergences and extend the discourse on archetypes to better link the global and the sub-global scales. We then discuss the importance of understanding the importance of sub-global heterogeneous worldviews (typical of bottom-up approaches), to promote a holistic understanding of the concept of 'consistency' in multi-scale scenario development

4.2 Material and methods

4.2.1 Scenario archetypes

The most recent analyses of scenario archetypes, use the words 'archetypes' and 'scenario family' interchangeably and focus on the qualitative interpretation of scenario assumptions. For example, (van Vuuren et al., 2012a) defines 'scenario archetypes' those scenario families that share similar storyline or logic which reflect in similar types of quantifications. The methodology in this study has a similar focus on narratives as van Vuuren et al. (2012a), i.e. on a qualitative analysis focusing on scenario logic. To build the methodology we start from the well-established assumption that existing scenarios tend to fall within archetypes (Hunt et al., 2012) and that archetypes can be interpreted using Cultural Theory (Boschetti et al., 2016). The starting point consists of the SSP global narratives which we chose to better address challenges to mitigation and adaptation than previous scenarios such as the SRES scenarios. Compared to other scenarios, the SSPs have the advantage of being separate from greenhouse gas emission scenarios and policy assumptions. That means that the uncertainties explored by the SSPs solely focus on socio-economic drivers. Because the SSPs consist of socio-economic and environmental (but non-climate) elements (O'Neill et al., 2015), they can be more easily mapped onto well-established archetypes of global socio-economic and environmental scenarios (Hunt et al., 2012). This study focuses on all SSPs, excluding SSP2 for two reasons: from a participatory point of view, the SSP2 scenario, also described as 'Middle of the Road' (O'Neill et al., 2017) lacks a clear identity and therefore is difficult to apply in a participatory setting (Kok et al., 2018), while being more useful for scenario practitioners seeking for 'closest to model baseline' scenario (O'Neill et al., 2017; Raskin, 2005). All the other SSPs (SSP1, SSP3, SSP4, SSP5) have a clear direction, at the global level, of socio-economic, technological, institutional and environmental trends. SSP1 is a sustainable scenario with effective collaboration across all actors of society, SSP3 is a socially fragmented and environmentally challenging scenario, SSP4 is a high-tech, green, institutionally and internationally effective scenario but with high inequality across and within society and SSP5 is a fossil-fueled, market- driven and reduced-inequality scenario. The scenario archetypes of Raskin (2005) and Hunt et al. (2012) support the hypothesis that the Global Scenario Group scenarios (as narratives of alternative world end states) still form a distinct set of archetypes. This holds for both global and sub-global scenarios (Hunt et al., 2012). The GSG archetypal social visions are four:

1. A world that evolves gradually as a result of market forces

2. A world that is influenced by a strong push for sustainability
3. A world with novel approaches to development new human values
4. A fragmented world with environmental and institutional collapse

Because of the similarities across global scenario narratives and drivers (STEEP), we first mapped the global SSPs against the GSG scenario archetypes, to test whether the SSPs fit with existing archetypes. We mapped the SSP narratives against the GSG scenario archetypes qualitatively, i.e. by interpreting narratives and qualitative trends against each other. This methodology, although simple and rather subjective, is well established in the scenario literature (van Vuuren et al., 2012a), especially when the narratives are limited to generic depictions of the future and take into account the same type of variables. In addition to the global SSPs, we also mapped five sub-global narratives, developed to be 'nested' within the global SSPs, to systematically assess the similarities and divergences at sub-global scales. The five case studies were selected to represent different scales and cultural contexts. The first scale is the pan-European scale, and it consists of the European version of the global SSPs, developed to be 'equivalent' to the global SSPs and transferable across scales (Kok et al., 2018). The second scale represents three geographically and culturally different regions within Europe: the Iberian peninsula, Scotland and municipalities in Hungary. The third scale represents the macro-region of Central Asia, consisting of a common narrative for five countries: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. For more details in the process of developing the scenarios we refer to Gramberger et al. (2015).

4.2.2 Archetyping the global SSPs

The archetypes pose a number of challenges, which have been identified at the global level (see Raskin (2005) and van Vuuren et al. (2012a)) and motivate the extension with more detailed information on sectors, actors and interactions (O'Neill et al., 2017; van Ruijven et al., 2014). In this section, we introduce the extended scenarios and the Cultural Theory as a tool to categorise firstly the global narratives and secondly compare the nested scenarios with their global archetypes. The basic assumption is that divergence from the global archetype is necessary, due to the inclusion of specific and local key drivers. However, the magnitude of required divergence depends on the relevance of global drivers such as international politics and policy, severity of local impacts and how local culture affects these perceptions. The challenges of the credibility posed by the global archetypes are directly related to the effect of specific contexts, not being captured at the global scale. From a case study point of view, Cultural Theory facilitates systematic interpretation of beliefs about society and nature in each scenario (Boschetti et al., 2016), considering that individual perceptions of climate change are more informed by subjectivity and personal worldviews than they are by science (Price et al., 2014).

Cultural Theory (Thompson et al., 1990), as an analytic tool, is used here to systematically analyse (and not to explain), divergences and similarities in the SSP narratives by classifying statements according to different worldviews and perceptions about ways of life and culture. According to Cultural Theory, four worldviews can be framed for perception of the world and how to act in it according to two dimensions: one about the degree of freedom of individual choice as bounded by the position in society (low or high 'grid') and one about degree of solidarity among members of society (low or high 'group'). The resulting worldviews are the hierarchist, the egalitarian, the individualist, and the fatalist (Table 4.1. For the classification we build on a 'coding' method developed by Beumer & Martens (2010). Scenario narrative statements are coded according to the four worldviews For classification, these statements are judged against established statements in the literature, summarised in Table 4.1 (Hoekstra, 2000; Middelkoop et al., 2004; O'Riordan & Jordan, 1999; Thompson et al., 1990; Van Asselt & Rotmans, 2002), on the worldviews about the key fundamental drivers (STEEP = Society, Technology, Economy, Environment and Policies).

The actual 'coding' is carried out individually by a team of three experts, who code all narratives according to the four worldviews, summarised in Table 4.1. For transparency, all individual results are reported in the Supplementary Material. Similarities and differences are discussed in the results section.

4.3 Results

4.3.1 Global SSPs and scenario archetypes

The global SSP worlds map well onto the Global Scenario Group archetypes (Figure 4.1): 'Great Transitions' (GT), 'Barbarisation' (B), 'Conventional-Policy-Reform' (PR) and 'Conventional-Market-Force' (MF) (Hunt et al., 2012; Raskin, 2005). The conventional market forces matches in most of the STEEP indicators: in both SSP5 and MF the emphasis is on cost-effective technological development, strong economic growth and faith in markets rather than social and environmental policies. The only mismatch is the perception of how society changes. While in both SSP5 and MF archetypes the emphasis is on individuals and consumerism, such trends are associated with a 'worsening of society' in MF (Hunt et al., 2012), but an increase in human and social capital in SSP5 (O'Neill et al., 2017). The GT and B archetypes match in all STEEP indicators with SSP1 and SSP3: in GT and SSP1 all indicators improve, while in B and SSP3 all the indicators worsen. The main diverging match is SSP4 and PR. Although they both assume strong government-led policies to achieve sustainability, the main difference is the interpretation of how such a top-down policy approach fares in society. Whereas PR assumes that social equity is an integral part of the sustainability policy (Hunt et al., 2012), SSP4 includes

Table 4.1: Statements on socio-economic, technology, economy, environment, policy (STEEP) indicators, selected from the SSP scenario element. The statements are interpretations for each element according to four worldviews (hierarchist, egalitarian, individualist, fatalist). Each statement refers to published literature, listed in the 'Source' column

STEEP	SSP element	Hierarchist	Egalitarian	Individualist	Fatalist	Source
Society	Human development/equity	Human nature is ignorant, therefore needs education. Social stability is desirable, also at cost of maintaining inequalities	Human nature is essentially good, communal and act accordingly. Equity and societal development	Individual and material self-interest are the motives of action. Success is personal responsibility	Human nature is unpredictable, more hostile than friendly	(van Asselt and Rotmans 2002 and Beumer and Martens 2010)
	Health investments	Health as human capital. Health services	Health as human asset.	Health as consumption good. Ageing	Unmanageable	(van Asselt and Rotmans 2002)
	Social cohesion	high within strata stratified, hierarchy (high group, high grid)	high, low predetermination by societal position of the individual (high group, low grid)	Low (but individual is not limited by externally imposed restrictions, i.e. low-group and low grid)	Low solidarity and high limits to individual choice (low group-high grid)	(from Thomson et al. 1990)
Technology	Development	High technology	Small-scale technology	Cheap/energy-efficient technology	No preference	(Hoekstra 1998 and Van Asselt and Rotmans, 2002)
Economy	Economic growth	Desirable with conditions	Undesirable	Desirable, unconditionally	Desirable but uncontrollable	(Hoekstra 2000)
Environment	Environment	Nature is wilderness to be tamed	Nature is fragile and wild.	Nature is robust and a resource	Nature is capricious and hazardous	(Beumer and Martens 2010)
	Land-use regulation/ management	Regulation. Supply-oriented management. Medium response to climate change	Protection. Demand oriented management. High response to climate change	Adaptation. Market regulation. Low response to climate change	Coping. Low response to climate change	(van Asselt and Rotmans 2002, and Beumer and Martens 2010)
	Agriculture	Middle productivity. Food demand similar to today	Low productivity. Food demand is lower: preference for vegetarian diet	High productivity. Food demand is high, preference for American style diet	No policy	(van Asselt and Rotmans 2002)
Policies	International cooperation	Controlled trade	Limited trade	Free trade	Trade is for the rich	(Hoekstra 2000, reference to water trade)
	Environmental policy	Reforestation policies, agricultural planning	Eco-forestry; eco-agricultural (low pollutant)	Intensive agriculture, protection of wood sector	No policies/ ineffective	(van Asselt and Rotmans 2002)
	Policy orientation	Stability	Nature preservation/ precaution	Growth of resources	Survival	(Beumer and Martens 2010)
	Institutions	Control-oriented	Prevention oriented	Market-oriented/ laissez-faire	Coping/passive	(Hoekstra 2000, Beumer and Martens 2010)

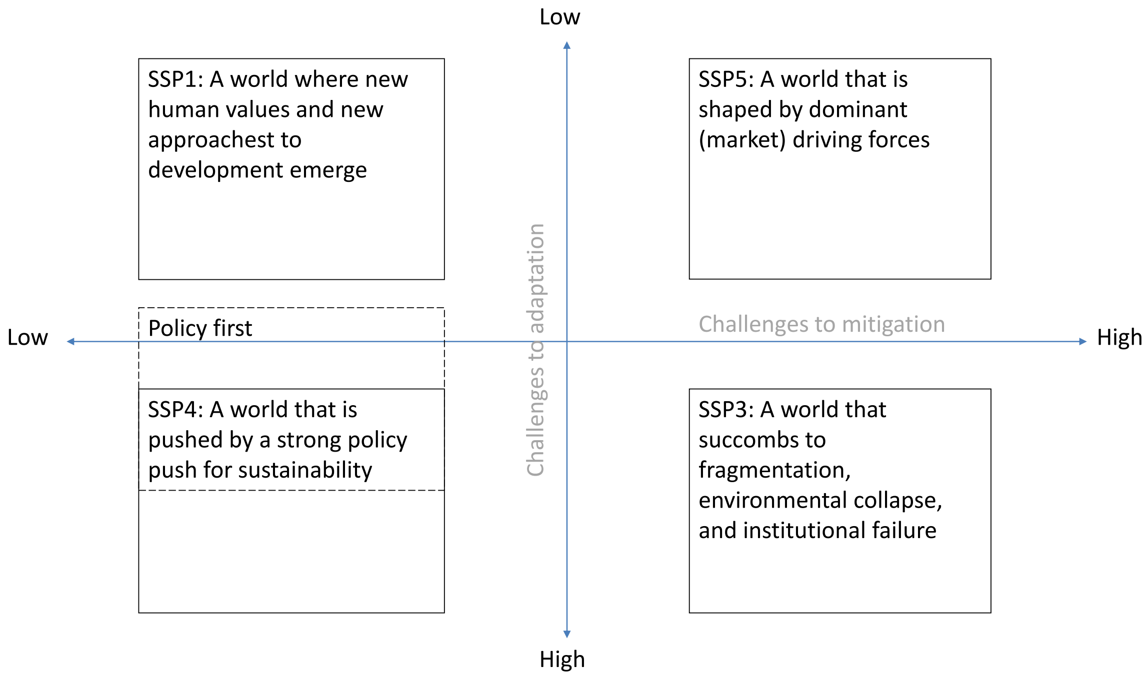

Figure 4.1: Four archetypical social visions of the world from the Global Scenario Group (adapted from Hunt et al. (2012); Raskin (2005), matching onto global SSPs (O'Neill et al., 2017). In grey: SSP axes. Dotted=partly unmatched archetype

a narrative for those excluded resulting in a dualistic scenario of effective international cooperation in a socially unequal world (O'Neill et al., 2017).

The finding that the global SSPs match with the GSG scenario archetypes supports this study‘s assumption that archetypes can be applied in heterogeneous social settings, such as stakeholder workshops, to frame a common understanding of the socio-economic and ecological world-scale scenarios. The divergence of narratives within the same archetype is due to differences in worldviews within local characteristics rather than considerations of internal consistency (Hunt et al., 2012; Price et al., 2014) or modelling framework requirements (Kebede et al., 2015). Because different worldviews and local information need to be included, nested multi-scale scenarios need to be developed by stakeholders. The methodology for developing multi-scale SSPs from global to local (e.g. national, regional, basin and municipality scale) to European SSPs (continental scale) consists of a 'nesting' process where local scenarios are contextualised in broader scale scenarios (Absar & Preston, 2015). The specificity of our approach, compared to Absar & Preston (2015), is that stakeholders are allowed to choose the drivers for their scenario and to match them afterwards into the global (or European) archetype (Biggs et al., 2007; Zurek & Henrichs, 2007). This has the advantage of leading to more relevant scenarios for the stakeholders, but has the disadvantage of resulting in numerous narratives. This disadvantage is reduced by professionally facilitating the stakeholder engagement (Gramberger et al., 2015). The resulting scenarios for all five case studies consist of a core of common elements to ensure a consistent process and products (Figure 4.1) while allowing representation of local and specific drivers as legitimately selected by stakeholders.

4.3.2 Worldviews across European scenarios

Combinations of worldviews for the five case studies in each scenario are presented in Figure 4.2. For the five case studies, we also added the analysis of the global narrative sketches from O'Neill et al. (2017) in the last row of each quadrant. The global narratives tend to be overall more homogeneous, with an overall agreement on one dominant worldview for >70% of the narratives. In SSP1 and SSP5, the worldviews are 100% egalitarian and individualist (Figure 4.2), which is in contrast with the more nuanced combinations across the other case studies. In SSP3 and SSP4, the mix of two worldviews, fatalist and hierarchist, is more representative of the nuances of the sub-global scale narratives. The sustainability scenario, represented by SSP1, has the commonality of the combination of egalitarian with, to a lesser extent, hierarchist worldviews in all case studies and in all time slices. Compared to all the other SSPs, SSP1 is the most homogenous scenario with the two worldviews being dominant across case studies. The hierarchist worldview is represented by statements in all scenarios on human and social development, green technology, equity and the value that nature is vulnerable. Hungary and Iberia are the most egalitarian of all. In the Scottish and pan-European case studies, hierarchist elements are stronger, reflecting the combination of high-green tech development, and belief in governmental regulation together with egalitarian values. Elements of individualism are also identified, related to statements on economic growth (European case study), and a focus on business and diversified economy (Scotland) and internationalisation in free market economies (both Europe and Scotland). The regionalisation scenario, represented by SSP3, presents common traits with dominant fatalist characteristics with a 'return to 'day-to-day' mentality' (in Scotland) and emphasis on surviving and coping in a fragmented society – in combination with egalitarian (Iberia and Hungary) or individualist (Europe) or both (Scotland). SSP4 is similar to SSP1 in that hierarchist and egalitarian views are commonly represented. The important difference, however, is that the egalitarian perspective is generally associated with reactions to the fatalist/hierarchist combination (also typical of SSP3): hierarchist and individualist in Europe; hierarchist, hierarchist-egalitarian and egalitarian-hierarchist in Iberia; hierarchist-individualist, individualist-fatalist and fatalist-egalitarian in Scotland; hierarchist-individualist and fatalist-egalitarian in Hungary. The fatalist-egalitarian perspective is dominant and visible in all local case studies as a result of perceived top-down enforcement strongly hierarchist governance components. Interestingly, this perspective is less visible in the European case study, where only the hierarchist component is visible with individualist elements. Lastly, SSP5 is very heterogeneous. A strong individualist perspective is present in the European case study, hierarchist

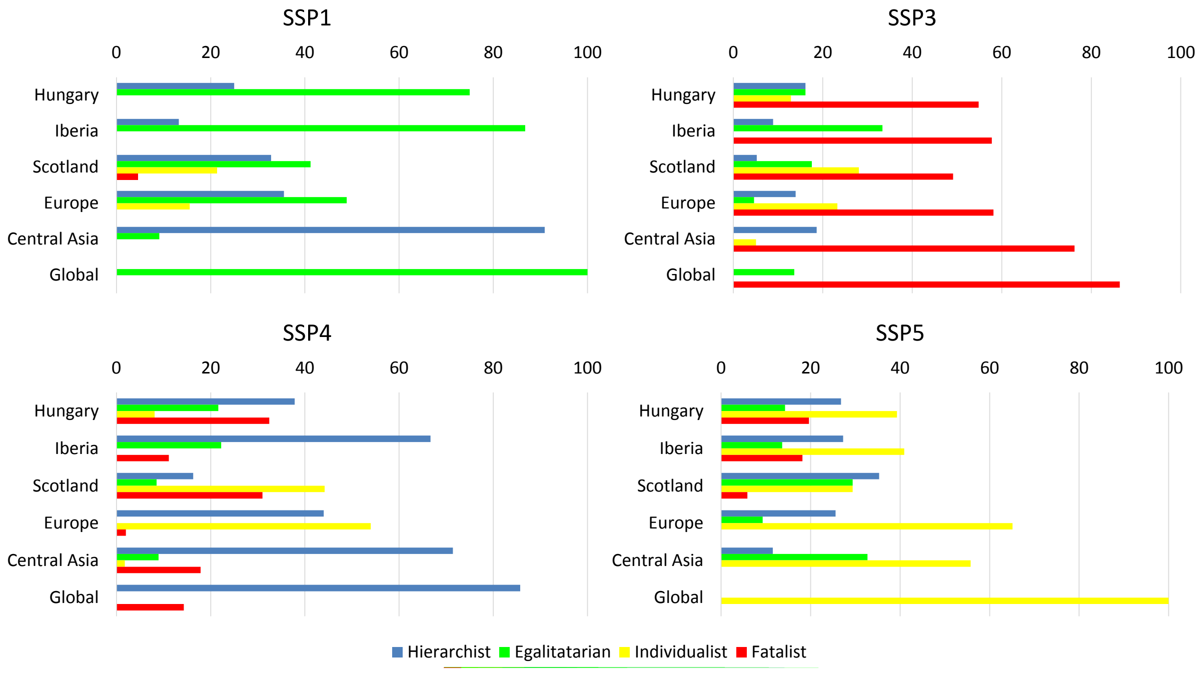

Figure 4.2: Frequency count (in %) of worldviews in the case studies (Hungary, Iberia, Scotland, Europe, Central Asia). The bottom case study is the analysis of the global sketch narratives from O'Neill et al. (2017)

and individualist are both dominant in Scotland and in the Hungarian and Iberian case studies, individualist and hierarchist perspectives shift to egalitarian and fatalist perspectives in the last time slices. Generally, the interpretation of the narratives and the combinations emerging from the analysis are aligned with the cultural context developed in Cultural Theory (Wildavsky, 2018) and with the identified forms of governments in the SSP narratives. The egalitarian/hierarchist combination, which emerged from SSP1, corresponds to the social democracy model, which is the closest option amongst the available ones to the participatory forms of governance sought in the SSP1 narratives; the fatalist/individualist and hierarchist/individualist combinations, emerging from SSP3 and, in some cases, SSP5 is associated to state capitalism which corresponds to the power of few actors and weak governments; fatalist/hierarchist, emerging from most SSP4, is typical of totalitarianism which is close to the top-down, repressive governments of all SSP4. Lastly, the association of individualism/egalitarianism corresponds to the American individualist belief that equal opportunity leads to to equal results (Wildavsky, 2018). This combination is less visible, and partly identified in European and Scottish SSP1.

Overall, the results highlight that the unequal global scenarios SSP4 and SSP3 are more nuanced, at the sub-global scale, than the archetypes of SSP5 (business-as-usual) or SSP1 (sustainability). Although, globally, the utopia-dystopia and, to a certain extent, business-as-usual archetypes tend to be well defined (Figure 4.1) according to the STEEP analysis, the dominant worldview and combinations are not as straightforward across case studies. The disagreement on social effects of the individualist SSP5, already identified in Hunt et al. (2012) is visible in the different interpretations of the scenarios, both across scales (Figure 4.2) as in the process of the analysis with larger disagreement on the interpretation than for other scenarios.

4.4 Discussion

4.4.1 Towards consistency of scenarios: Archetyping Shared Socio-economic Pathways across scales

This study assessed the consistency of Shared Socio-economic Pathways with earlier scenarios and across scales. To this end, we archetyped the global SSPs in two ways. First, we related the SSPs with the scenario archetypes developed by Hunt et al. (2012). The results show a good match between the two, with only few deviations. This result indicates that while the SSPs better address the uncertainty space of challenges to mitigation and adaptation, they extend common underlying assumptions in a manner that is consistent with previously developed global scenarios (Harrison et al., 2018b; Hunt et al., 2012; van Vuuren et al., 2012a). The coding exercise is subjective in nature (e.g. van Vuuren et al. (2012a)), and therefore a choice was possible between a comprehensive (explanatory) model and a simple (comparative) model. Because the purpose of this study is to compare worldviews across case studies, we chose for the second option, Cultural Theory, as stated in the method. Cultural Theory cannot explain trends for two reasons. Firstly, four worldviews constitute a too coarse model and a larger number of worldviews and inclusion of social learning would be more realistic (Pahl-Wostl, 2008). Secondly, driving forces in Table 4.1 have been selected depending on available information in existing literature. A consequence is that several driving forces of the SSPs could not be categorised in the four worldviews For example, key uncertainties of the SSP scenarios relate to international cooperation and population growth, which cannot be directly related to a specific worldview. We avoided additional assumptions and utilised the existing categorisation, therefore excluding from the coding exercise information that does not relate directly to existing literature. Two main uncertainties emerged in the exercise process. The first was the interpretation of worldviews that do not fit, overlap or partly mismatch in the typologies of the Cultural Theory model, such as the 'environmentally care-free' attitude which was attributed to either fatalist or individualist worldviews and the interpretation of large economic development and strong governmental investment of most SSP5 narratives. The second was that the focus of the narratives drove the coding colour, especially in SSP3 and SSP4. For example, in the same story, the colour coding would change if the focus was on the 'haves' (interpreted as hierarchist or individualist) or 'have-nots' (generally fatalist, but also egalitarian when proactive). The emphasis on strong government (or lack of it) has also an effect on the balance of the worldviews within the same case study: hierarchist worldviews are comparatively strong in SSP1 and SSP5 for Scotland among all regions assessed here, they are lowest in the Scottish SSP3 and SSP4. The heterogeneity of worldviews shows that contemporary downscaling of SSPs to different regional contexts takes into consideration regional variation of worldviews This effect, however, is inconsistent across SSPs. This result calls the consistency of contemporary regionalization of SSPs into question. Furthermore, insights into the heterogeneous worldviews have implications for the use of SSPs in policy development. For instance, contemporary policy development based on scenarios with strong individualist worldviews are less likely to succeed in countries with strong egalitarian values (Corner et al., 2014). However, these mismatches also indicate the different foci, cultural bias and beliefs held by stakeholders, even at a similar geographical scale. For example, even in the most homogenous SSP1 archetype the Central Asian narrative is more focused on a much stronger government intervention to drive sustainability compared to the European (and global) SSP1. These mismatches also indicate that obvious and simple relations across socio-economic (and, consequently, other STEEP) variables, identified at the global scale, should be carefully interpreted both in multi-scale scenario development and quantitative impact analyses. The narratives and the multiple worldviews in sub-global SSPs show the different needs for the sustainable archetype world, with emphasis on not only egalitarian worldviews but also hierarchic and individualist approaches. The analysis also showed that more detailed narratives, such as Scottish SSPs, are characterised by more detail and realism which made the coding more difficult but also more nuanced and differentiated which was in stark contrast to the simple global SSP narratives. Scenario narratives are not only archetypes, but contain information about different context needs, for addressing those in strategies, and about the main actors that need to take action. The analysis of worldviews embodied in scenario archetypes has highlighted sources of (in)consistencies in scenarios across scales. Consistency of scenario archetypes across scales can be strengthened by developing scenarios in a bottom-up manner to match global archetypes, i.e. by using and refining global scenario archetypes in contextualized scenario development. For instance, (Pereira et al., 2018) developed archetypal scenarios of the Anthropocene in southern Africa through transformative visioning. Also, in a regional watershed scenario project in Wisconsin, USA, (Wardropper et al., 2016) found that local perspectives on how change occurs emphasized and contextualized three of the global archetypes.

4.4.2 Relating scenario archetypes to other archetype analyses in sustainability research

Archetypes have also been used for pattern identification and diagnostic purposes in sustainability research, with nuanced meanings and different research practices (Oberlack et al., 2018). Pattern-identifying studies reveal archetypes inductively by using comparative or statistical methods for analyses of empirical data (Levers et al., 2015; Oberlack et al., 2016; Sietz et al., 2017). Archetypes function as diagnostic tools, if well-established knowledge on archetypes is used to diagnose the system of concern or test hypothesized causal effects in new empirical research (Banson et al., 2014; Mokhtar & Aram, 2017). In both functions, archetypes refer to empirically validated, recurrent patterns of the phenomenon of interest (Eisenack et al., 2006). Scenario archetypes, by contrast, refer to a set of internally consistent scenarios with common narratives and characteristics, often developed with stakeholder engagement in futures research (Hunt et al., 2012). Better interplay of those strands of research could strengthen the knowledge claims embodied in archetypes in at least two ways. First, scenario archetypes could help frame the research questions of interest for empirical and diagnostic archetype research. Second, empirical archetype analyses could help validate the causal effects or mechanisms assumed in scenario archetypes.

4.5 Conclusions

This study raises the attention on the relevance of existing archetypes for scenario narratives developed across multiple scales. Archetyping narratives has guided the analysis through embedding narratives within a broader or narrower context. However, the development of scenario archetypes needs to better address the different scales of application of scenarios, looking jointly at global and sub-global scales. Scenario narratives can be better employed to capture complexities at multiple scales, beyond the STEEP approach. Global narratives can take into account the bottom-up development of the same archetype at sub-global scales capturing their emerging patterns which, in turn, provides an appropriate context at the sub-global scale.

Chapter 5

Advancing the use of scenarios to understand society's capacity to achieve the 1.5 degree target

This chapter is based on:
Pedde, S., Kok, K., Hölscher, K., Frantzeskaki, N., Holman, I., Dunford, R., Smith, A. & Jäger J. (2018). Advancing the use of scenarios to understand society's capacity to achieve the 1.5 degree target. *Under review in Global Environmental Change*

Abstract

With a range of potential pathways to a sustainable future compatible with the Paris Agreement 1.5°C target, scenario analysis has emerged as a key tool in studies of climate-change mitigation and adaptation. A wide range of alternative scenarios have been created, and core amongst these are five socio-economic scenarios (Shared Socio-economic Pathways or SSPs) and four emission scenarios (Representative Concentration Pathways or RCPs). Whilst mitigation scenarios have been developed for each SSP-RCP combination, describing the actions necessary to match the climate pathway of the RCP (the Shared Policy Assumptions, or SPAs), there has not yet been a systematic approach to address whether and how these actions can be enabled in practice. We present a novel and transferable framework to understand society's capacity to achieve the 1.5°C target, based on four participatory case studies using the SSP-RCP scenarios. The methodology builds on a framework for categorising different types of societal capitals and capacities and assessing their impact on the potential to implement different types of mitigation actions. All four case studies show that SSP1 has the highest potential to reach the target. Although environmental awareness is high in both SSP1 and SSP4, continued social inequalities in SSP4 restrict society's capacity to transform, despite economic growth. In the two least environmentally-aware SSPs, SSP3 and SSP5, the transformation potential is low except in case studies where SSP5 has higher capitals and lower social inequality. The study highlights that techno-economic assessments of climate strategy need to be complemented by consideration of the critical role played by social and human capital, and by societal capacity to steward natural resources, orchestrate positive change, unlock new behaviours and transform existing institutions. These capitals and capacities are essential to enable the rapid innovation, behavioural change and international co-ordination needed to achieve the target.

5.1 Introduction

The ambition of the Paris climate agreement to limit global temperature increase to 1.5°C by 2100 creates a pressing demand to find ways to achieve this goal (Rogelj et al., 2016; Hulme, 2016). The IPCC special report on the 1.5°C target presents four alternative pathways, which all involve major transformation of the energy system together with large-scale changes to human behaviour and land-use (IPCC, 2018). These changes pose major political challenges, and some authors argue that the 1.5°C target will be unattainable without resorting to high-risk, large-scale geo-engineering (Akimoto et al., 2017). Others, however, claim that limiting global temperature increases to 1.5°C is possible through action-led, societal transformation (Hermwille, 2016; O'Brien, 2015; Rockström et al., 2017; Tàbara et al., 2013, 2018; Westley et al., 2011). With such different potential pathways to a sustainable future, scenario analysis has emerged as a key tool in studies of climate-change mitigation and adaptation, and a wide range of alternative socio-economic and climate scenarios have been created (Akimoto et al., 2017; Friedlingstein et al., 2014; Rogelj et al., 2009, 2015, 2016). Core amongst these are the five socio-economic scenarios (Shared Socio-economic Pathways or SSPs) and four emission scenarios (Representative Concentration Pathways or RCPs) which have been developed in parallel (Moss et al., 2010) and are intended to be independent yet complementary (O'Neill et al., 2016; van Vuuren et al., 2014). The RCPs describe the evolution of future greenhouse gas concentrations and associated climate impacts without any assumptions on mitigation actions. The SSPs explore different socio-economic futures and the challenges they present for climate mitigation and adaptation (O'Neill et al., 2015) as socio-economic factors enable or constrain the actions needed to meet climate and sustainability targets (O'Neill et al., 2016). For example, scenarios including high investment in green technology and low energy demand reduce the additional effort required for climate mitigation, whereas scenarios assuming high levels of human well-being and flexible institutions may enable easier adaptation to climate change (O'Neill et al., 2017). For each SSP, a baseline scenario describes a future socio-economic pathway assuming no climate change and no additional climate policy actions (Riahi et al., 2017). For each SSP-RCP combination, a mitigation scenario has been developed that describes the additional actions that would need to be taken (beyond the SSP baseline) to match the climate pathway of the RCP, consistent with a set of Shared Policy Assumptions (SPAs) which describe the climate mitigation policy environment for each SSP (Riahi et al., 2017).

Whilst the SSP-RCP scenario matrix has been designed to be relevant to end-users (such as decision-makers, policymakers and practitioners) and consistent with climate policy assumptions (Carlsen et al., 2013; Kriegler et al., 2012, 2014), there are limits to its utility in decision-making contexts for several reasons. Firstly, the SSPs were not designed as a direct tool for policy-makers, but only for researchers to produce climate assessments that will then be shared with policy-makers (O'Neill et al., 2015a). As a result, policy-makers report "poor understandability of scenario data" (Pilli-Sihvola et al., 2015). Secondly, the SSPs may not be sufficiently context-dependent or relevant to different situations (e.g. a different spatial scale or context (Nilsson et al., 2017)). Thirdly, externally-created scenarios may not be well connected to the users' worldviews, impacting their understanding of and buy-in to the scenarios (Lempert, 2013). There is therefore a need for better connecting the knowledge of climate researchers and policy-makers (Klein & Juhola, 2014; Pilli-Sihvola et al., 2015).

In this study, we advance the use of combined SSP-RCP scenarios to explore systematically society's ability to achieve the 1.5°C target, by identifying the potential to transform as a function of capitals and capacities in the SSP-RCP combinations. Our main goal is to clarify the implications of the combined scenarios, both in terms of contextual opportunities and constraints and the ability of actors to achieve societal change, to better inform decision-making. The scenarios have been co-developed with stakeholders as part of a methodology targeted at addressing policy-relevant issues in a series of nested case studies from global to European sub-national scale. The methodology involved identifying the elements that 'enable' climate action in each SSP through an assessment of i) the five capital stocks available for society to draw upon (human, social, natural, financial and manufactured capital), and ii) the four types of agency capacities (stewarding, unlocking, transforming and orchestrating) through which actors are able to leverage these capitals and enact change. To this end, we developed a novel, cross-scale and transferable approach combining capitals (as indicators of the material and non-material resources available) with actors' collective capacities for change, consistent with each SSP-RCP scenario and each case study. We discuss how this framework of capitals and capacities provides relevant information to decision-makers on the possible future challenges and opportunities associated with the 1.5°C target.

5.2 Methodology

This study builds on the SSP-RCP framework to identify how different scenarios enable or constrain the achievement of the 1.5°C target, for each of four case studies. We start with the recognition that the 1.5°C target requires strong action, involving not just technological and social development but also institutional change, behavioural change and land-use change, consistent with the level of mitigation action reported in integrated assessments globally (Riahi et al., 2017) and regionally (van der Zwaan et al., 2016). The IPCC Special Report on 1.5°C Summary for Policymakers (IPCC, 2018) highlitghts the importance of this framework, by stating that

> "strengthened multi-level governance, institutional capacity, policy instruments, technological innovation and transfer and mobilization of finance, and changes in human behaviour and lifestyles are enabling

conditions that enhance the feasibility to achieving the 1.5°C target".

This requires moving beyond the original distinction between "challenges to adaptation and challenges to mitigation" that defines the uncertainty space of the SSPs, and adopting a more holistic approach geared towards a fundamental societal transformation (Westley et al., 2011; Feola, 2015; Hermwille, 2016; Gillard et al., 2016; IPCC, 2018). Societal transformation must be driven by different actors, defined as both individuals or organisations representing different sectors (governments, communities, market and third sector) with the capacity to change the state of human and natural systems (O'Brien, 2015, 2016; Avelino & Wittmayer, 2016). As these actors are embedded within societal structures (e.g. formal and informal institutions, social networks, resource distribution), their capacities are manifest in the extent to which they are able to mobilise, create and change these structures (Giddens, 1979). We therefore base our methodology on assessing two key sets of indicators:

1. Stocks of five types of capital: human, social, natural, manufactured and financial, with a focus on human and social capital because they underpin the potential for transformational societal change;
2. Four types of capacity that give actors the agency to mobilise, create and change the stocks of these five capitals: stewarding, unlocking, transforming, orchestrating.

The main goal of our methodology is to identify which stocks of capital can be mobilised by which types of actors in each scenario combination. Whether and how actors are able to mobilise capitals is analysed by drawing on a systematic framework of their capacities for transformation Hölscher (2018a). The actors are identified inductively in the scenario narratives, and are integrated into the capacity analysis. The first step of our methodology was to determine what capitals and capacities need to be assessed and to link them to potential mitigation actions in a theoretical framework (Section 2.1). We then applied this framework within four case-studies (Section 2.2). In the results (Section 5.3) we interpret the joint impact of the capacities and capitals on the potential for society to meet the 1.5 °C target under each scenario, and show how these findings relate to Integrated Assessment Modelling approaches.

5.2.1 Capital stocks and societal capacities that constrain and enable actions towards the 1.5°C target

'Capitals' are defined as stocks yielding a benefit valued by humans (Porritt, 2007). The concept of capitals is useful for providing information on the enabling conditions in scenarios. They are straightforward (Tinch et al., 2015) and provide a more systemic understanding than economic- or population-based indicators. In this study, we consider five capitals: human (education, knowledge, health), social (individual relationships, societal trust, institutions and networks), manufactured (technology and infrastructure), natural (ecosystems) and financial (markets) (Jäger et al., 2015; Porritt, 2007; Tinch et al., 2015). Whether and how the capital stocks can be mobilised, created and changed to achieve the 1.5 °C target essentially depends on questions of agency (Westley et al., 2011; Gillard et al., 2016). In other words, who in the scenario narrative has abilities to mobilise, create and change societal structures (e.g. formal and informal institutions, social networks), knowledge, beliefs and resources for developing and implementing strategies and actions (Westley et al., 2013). We employ the concept of capacities for understanding the abilities of actors in the scenarios to effectively mobilise, create and change capital stocks. At the same time, capital stocks can constrain or enable actors in using their capacities. Different types of capacities can be identified that fulfil distinct functions for developing and implementing transformative strategies and responding to different types of transformation dynamics: stewarding, unlocking, transforming and orchestrating (Table 5.1) (Hölscher, 2018a,b). These capacities build on a literature review of sustainability transitions and resilience approaches that are concerned with transformative change and agency (Grin et al., 2010; Loorbach et al., 2017; Folke 2016; Olsson et al., 2014; Westley et al., 2013). The three levels of capacity defined in Table 5.1 are based on the authors' interpretation and synthesis of the literature review and are subsequently used during the scenario analysis.

The theoretical framework facilitates the integration of human and societal dimensions of agency (via the capacities) into the analysis of adaptation, mitigation and transformation. To do this, we divide actions into four broad categories: technological, institutional, lifestyle and land-based, based on expert judgement of our interdisciplinary authorship team. In our framework, these categories each depend on a different mix of capital stocks, and require the relevant actors and capacities to mobilise these stocks (Figure 5.1). Using mitigation action as an example, technological mitigation involves developing and investing in new and improved technologies such as energy supply and energy efficiency, carbon capture and storage and (in some scenarios) 'geo-engineering', requiring high stocks of financial and manufactured capital as well as social and human capital for technical expertise. This therefore links with the transformative capacity for innovation and learning (capacity 'T' in Figure 5.1). Institutional action includes governance-related actions such as taxation, regulation and market reform (e.g. carbon trading). Lifestyle change includes individual and collective actions that reduce demand for energy and resources, including dietary change and waste avoidance. Both institutional and lifestyle change require high levels of social and human capital. To mobilise these capitals towards institutional change, all four capacities are required. For individual lifestyle change, the focus is on the capacity to build flexible networks of individuals (stewarding), social innovation (transforming) and effective counter-movements (unlocking). Land-based mitigation (including reduced emissions from agriculture, increased carbon storage and sequestration in soils and vegetation, and bioenergy with or without carbon capture and storage) requires integrated and long term planning as well as know-how (stewarding and

Table 5.1: Interpretation of capacities to measure enabling and disabling conditions in SSP-RCP combinations. The literature reviewed to assess the level of capacity is indicated in column 1, below the definition of each capacity

Capacities	Low	Medium	High
Stewarding Ability to anticipate, protect and recover from disturbances while exploiting opportunities beneficial for sustainability (Chapin et al., 2010; Folke, 2006) (Garmestani and Benson, 2013)	- Low social cohesion - Risk-numb: No desire for long-term planning and reactive risk management - Coping, no reflexivity	- Communities of interest without collective identity. - Risk-averse: Mid-term planning to control risk - Fragmented know-how (without knowledge integration)	- Strong social networks and supportive social contexts - Proactive long-term integrated planning. Risk taking and uncertainty embracing - Collective memory and learning (reflexivity, integration of knowledge)
Unlocking Ability to recognise and dismantle drivers of unsustainability and path-dependencies (Geels, 2014; Kivimaa & Kern, 2016)	- Acceptance and support of existing institutions, values and practices. - Powerful interest networks to maintain status quo	- Uncoordinated counter-movements - Competing interest networks along with weaker counter-networks	- No support for status-quo - Effective opposition networks
Transforming Ability to create novelties and embed them in practices (Frantzeskaki et al., 2012; Westley et al., 2013) (Raven et al. 2010)	- Low investments in and no leadership for innovation	- Innovation and competition for specific interests	- Leadership for innovation - Learning from tested solutions (e.g upscaling and replicating)
Orchestrating Ability to coordinate multi-actor processes to maximise synergies (Chan et al., 2015; Frantzeskaki et al., 2014; Hodson & Marvin, 2010)	- No shared development goals and frameworks - Low collaboration across scales and sectors - No transparency in decision-making	- Shared and long-term development goals between small groups - Collaboration limited by competition across scales and sectors - Good governance but no political culture	- Shared and long-term development goals - Collaboration across scales and sectors - Good governance, with engaged political culture

transformative capacities). The crucial point in the framework is that the level of societal transformation required to meet the 1.5 °C target cannot be achieved through only one type of action, e.g. technological action alone, due to spillovers and trade-offs (IPCC, 2018). According to this reasoning, mobilising capital stocks to enable the full spectrum of actions requires all four types of capacity. However, the societal context (in this study, the SSP-RCP combinations) determines which capacities and which types of action will be feasible.

Action Types	Capitals					Actors				Capacities			
Technological	**S**	**H**	N	**F**	**M**	**G**	C	**M**	**T**	S	U	**T**	O
Institutional	**S**	**H**	N	**F**	M	**G**	C	M	T	**S**	**U**	**T**	**O**
Life-style	**S**	**H**	N	F	M	G	**C**	M	**T**	**S**	**U**	**T**	O
Land-based	**S**	**H**	**N**	F	M	**G**	**C**	**M**	**T**	**S**	U	**T**	**O**

Figure 5.1: Elements of the theoretical framework to analyse the potential to reach the 1.5 °C target. Capitals are social (S), human (H), natural (N), financial (F), manufactured (M). Actors are governments (G), communities (C), markets (M), third sectors such as NGOs and research (T). Capacities are: stewarding (S), unlocking (U), transformative (T), orchestrating (O). The shaded cells are capitals, actors and capacities which are most influential in determining the effectiveness of a given mitigation type

5.2.2 Case studies: participatory development of SSPs for the European region, Iberia, Hungary and Scotland

This theoretical framework has been applied in four case studies: Europe as a whole (the 2013 EU 27 plus Switzerland and Norway); Scotland, the Iberian Peninsula (Spain and Portugal) and two municipalities in Hungary. SSPs were co-produced with stakeholders for each case study: the 'Eur-SSPs' for Europe and the three 'local SSPs': Scottish, Iberian and Hungarian.

The European and Scottish case studies focus on the cross-sectoral impacts of land-use and climate change, linking urbanisation, agriculture, water resources, forestry and biodiversity sectors (Kok et al., 2018 and Harrison et al., 2018). Both European and Scottish case studies build from previous scenario work in the CLIMSAVE project (Harrison et al., 2015) and have been further developed to include the socio-economic and climate drivers of the SSPs and RCPs (Kok et al., 2018). The Iberian and Hungarian case studies focus on the sectors and impacts that are more relevant to local societal interests. For Iberia the focus is on impacts on agro-forest systems and governance of transboundary river basins (Tàbara et al., 2018) while for Hungary the focus is on impacts of population dynamics on urban land-use and health (Li et al., 2017). The scenarios have been developed by engaging stakeholders to develop the scenario narratives and review the analyses (Tàbara et al., 2018), therefore ensuring that scenarios are diverse enough to be relevant for and driven by stakeholders but still comparable in terms of structure and process. In line with van Ruijven et al. (2014), the local SSPs are consistent with the global SSPs, while allowing for specific characteristics, depending on the stakeholders' choice of key drivers of change and their interpretation of the global and Eur-SSPs. The local and Eur-SSPs describe a range of challenges to adaptation and mitigation, which have been interpreted as varying levels of inequality and carbon intensity (Figure 5.2). Eur-SSP1

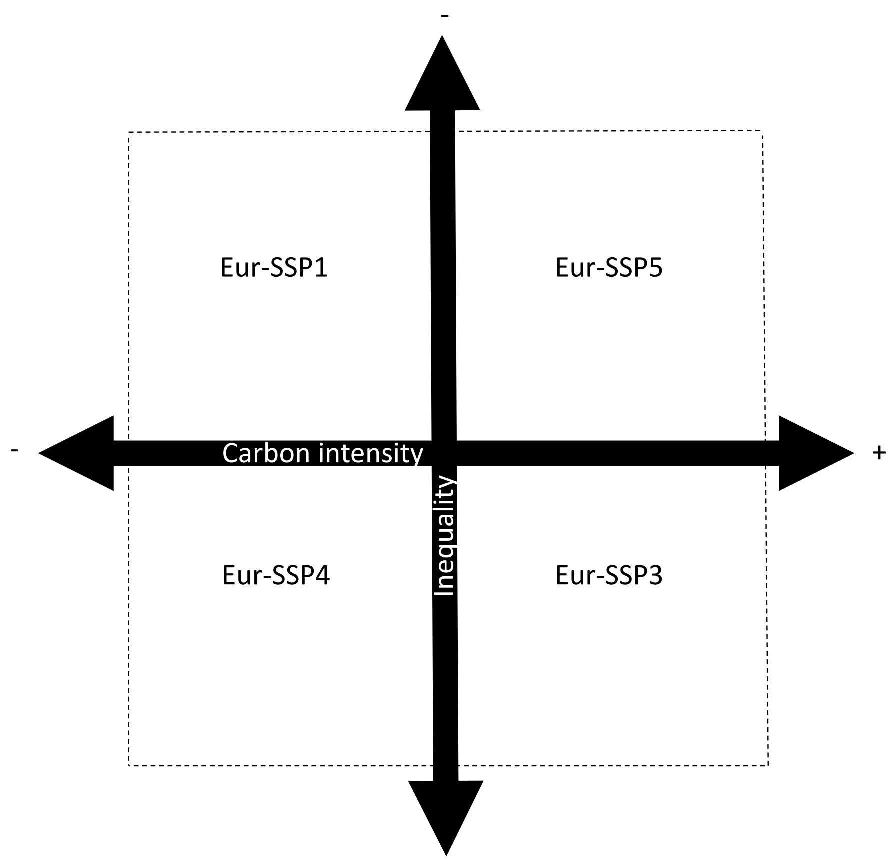

Figure 5.2: Interpretation of challenges to adaptation (inequality) and mitigation (carbon intensity) of the European SSPs

and Eur-SSP5 develop into relatively inclusive societies, whereas Eur-SSP3 and Eur-SSP4 are highly unequal. Eur-SSP1 and Eur-SSP4 are less carbon-intensive than Eur-SSP3 and Eur-SSP5. A European SSP2 was not developed as it was interpreted to converge to the average of the other scenarios, and therefore was less suitable than the other SSPs for identifying alternative capacities and challenges. We refer to (Kok & Pedde, 2016) for the Eur-SSPs and local SSPs and to the IMPRESSIONS Deliverable (Kok & Pedde, 2016) for the sketch of all the SSP narratives for all case studies.

This conceptualisation is consistent with the original separation between SSPs and SPAs. Actions (SPAs) are not included in our scenarios (SSP-RCP) but are enabled or constrained by the differing capacities of the actors and capitals in each SSP-RCP. In this reasoning, SSP-RCP represent the societal potential to transform, and the SPAs represent societal action towards transformation. The SSP-RCP context thus needs to contain information on what conditions exist to enable (or constrain) the additional actions needed to reach the 1.5°C target.

The participatory process to develop the Eur-SSPs and local SSPs consisted of workshops in which stakeholders addressed the exploratory question: "what could happen?" (Börjeson et al., 2006), in order to develop trends for capital development within three time slices (2010-2040, 2040-2070 and 2070-2100). The workshops were professionally facilitated (Gramberger et al., 2015) to produce iteratively trends for capitals consistent with the scenario narratives. Subsequently, the narratives were interpreted to assess the capacities qualitatively against the categories and levels of capacities of Table 5.1. The capacities interpreted for each scenario narrative were then combined with the stakeholder-derived capital trends to assess the potential of society to transform to achieve the 1.5°C target. The potential was then interpreted against the categories of mitigation actions to define what mitigation is feasible and this was compared with potential identified with the global SSP-RCP mitigation scenarios (Riahi et al., 2017). The Eur-SSPs and local European SSPs paired with the respective RCP can be used to structure "what could happen" and map the trend onto a theoretical space in time (until 2100) and to show the distance from "what do we want", i.e. the 1.5°C target (Figure 5.3). The pairing of each SSP and RCP was chosen to reflect the challenges to mitigation. SSP1 and SSP4 have lower challenges to mitigation so they were paired with RCP4.5, while SSP3 and SSP5 were paired with RCP8.5.

5.3 Results

5.3.1 Potential to achieving the 1.5°C target in each scenario combination

The results show what capacities and capitals are available in the SSPs to transform society to function consistently with the requirements to achieve the 1.5°C target. The availability of capitals and capacities in each case study is summarised in Figure 5.4.

In all case studies, SSP1 achieves the highest capitals and capacities because of the active participation of all types actors (market, research, government and third sector) towards sustainability. In the Eur-SSP1, strong international cooperation and institutions, most importantly the political integration of European countries in view of shared sustainability priorities, enable the establishment of multi-level governance and an early shift towards a sustainability focus. European institutions also play a positive role in enabling a strong early push towards sustainability in the Hungarian and Iberian SSP1 (a "European social framework" in Iberia and the European Union in Hungary), in combination with bottom-up participation and municipality-level sustainability-oriented investments and governance. Only in the Scottish SSP1 the trigger towards sustainability is not directly enabled by the European Union but rather by the Scottish government.

The quick transition towards sustainability in SSP1 leads to the maintenance and

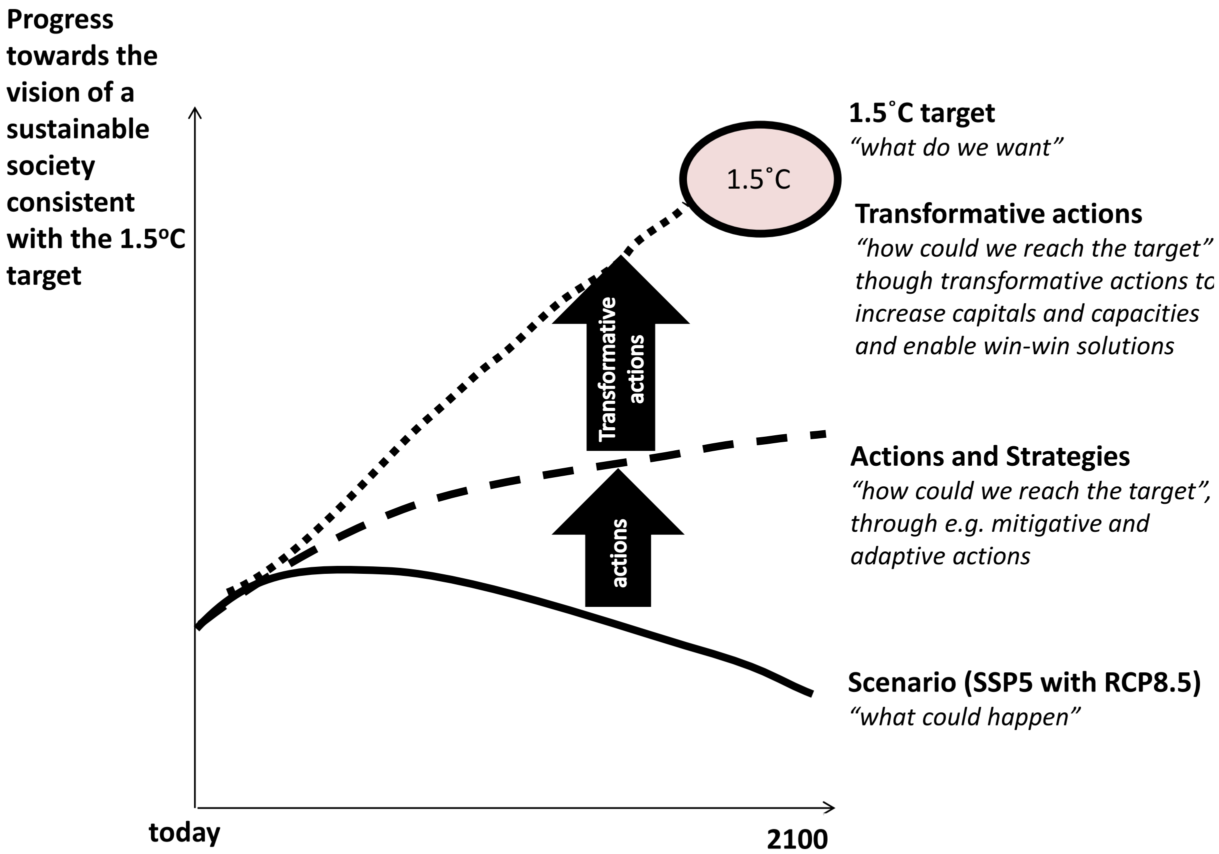

Figure 5.3: Conceptualisation of scenarios as context to develop mitigation and adaptation pathways to reach a desired vision in 2100. The actions to develop sustainable pathways towards the vision build from the scenario and are scenario-contextualised in time

Figure 5.4: Conceptualisation of scenarios as context to develop mitigation and adaptation pathways to reach a desired vision in 2100. The actions to develop sustainable pathways towards the vision build from the scenario and are scenario-contextualised in time

further steady creation of capacities until 2100. Societal and environmental awareness is generated early in the scenario, resulting in high levels of human and social capital and thus in high orchestrating, transformative and stewarding capacity. The unlocking capacity that has supported the establishment of effective counter-movements and social innovation decreases towards 2100, as the new sustainability paradigm is established and the importance of opposition networks decreases. In all case studies SSP1 gets close to the 1.5 °C target but there are still some challenges that need to be addressed to fully achieve the target and avoid trade-offs. Nonetheless, SSP1 is the scenario with the highest potential to achieve the 1.5 °C target .

In SSP3, capacities and capitals decline in all case studies. The cause of the overall decrease of capacities is the focus on short-term governance, weak leadership and low investment for innovation. The lack of reflexivity and learning from tested solutions results in generally low stewarding, transformative and orchestrating capacities, apart from the Scottish case study, where governance and innovation are managed by large companies. However, unlocking capacity brings the potential for novel networks, unconstrained by top-down enforcement given the lack of leadership. The potential for a reversal of the status-quo is limited by the general lack of coordination and competing interests of counter-movements. In SSP4, capacities tend to average at medium level for two main reasons: overall competition and a combination of low capacity for local actors with higher capacity of actors at national or European level. In Europe, Iberia and Scotland, powerful multinationals exert a stabilising influence which enables cooperation (orchestrating capacity) and innovation (transformative capacity). These capacities are however exercised in a very top-down manner due to the concentration of power, and learning is limited due to competition, political and economic power-grabbing and large-scale social exclusion. In Hungary, social networks and reflexive learning together with the existence of counter-movements until 2070 generate high stewarding and unlocking capacity, enabling communities to push for sustainability and resilience. At national level, however, the focus is on coping , low investments, and rigid top-down maintenance of status throughout the whole scenario, de facto decreasing the potential of local actors.

SSP5 shows the greatest variation of capitals and capacities between case studies. Natural capital is low in all SSP5 case studies, while human and social capitals are high in Europe and Iberia but low in Scotland and Hungary. Although all SSP5 case studies share the common traits of economic development and social equality, the effect of individualism, economic growth (linked to high resource exploitation and consumption) and environmental damage were perceived differently in different case studies. Scotland and Iberia end up with medium unlocking capacity, consistent with lack of support for the status-quo and effective opposition. Because other capacities and/or capitals are limited, overall potential remains close to ‘medium’, except for Europe (and Scotland, to an extent) where potential is ‘high’ due to the availability of knowledge, capitals, technology and preparedness to shift to 're-emergence of investments in renewables' when needed.

In Figure 5.5, we show the overall potential of the European SSPs to transform societies towards a 1.5°C-consistent world as a function of capitals and capacities. Letters representing each of the four capacities (S, U, T, O) are plotted on a scale of high-medium-low (according to the definitions in Table 5.1) on the x-axis, and their position on the y-axis is determined by the combined level of human and social capital (the capitals that underpin social transformation). The colour of the boxes indicates how these levels of capitals and capacities combine to determine society's overall potential to achieve the 1.5 °C target in each scenario, from 'very low' to 'very high'. For example, in the Eur-SSP1 the potential for achieving the 1.5 °C target is 'very high' as a result of 'high' social and human capitals and 'high' stewarding, orchestrating and transformative capacity, whereas Eur-SSP3 results in 'low' potential because of overall 'low' capitals, 'low' stewarding and orchestrating capacity, 'medium' transformative capacity, and 'high' unlocking capacity.

Because of the high levels of both capacities and capitals, SSP1 has generally 'very high' potential to transform. However, because people are generally more satisfied with this world and there is less impetus for transformative change, this manifests in medium unlocking and 'high' (rather than 'very high') transformative capacities. In contrast, SSP3 has 'very low' or 'low' potential in all case studies, as the capitals and capacities are low due to the power of 'elites' coupled with conflicts and disparities. However stewarding, unlocking and orchestrating capacity can grow as people organise themselves into communities of interest to counter the status quo, and to share resources such as food (as in the Hungarian and Scottish case studies). This provides some stability and decreases conflict, albeit with larger inequalities than at present. In the European SSP3, the European Union collapses but 'richer (ex) Member States' can still afford clean technology, clean water, energy and health services.

SSP4 tends to have 'low' or 'medium' potential across all case studies. This is because cohesion, collaboration and networks exist within social classes (unlike the more conflictual SSP3 scenarios). Capacities and capitals are high for the elite, who adopt green technology, but low for the majority. This stratification and social exclusion limit the capitals and capacities, and thus the overall potential to transform. Despite generally having higher capitals than SSP3, due to more stability and economic growth, the overall potential of SSP4 is similar to or only slightly higher than SSP3 because the capacities tend to change little over time.

The SSP5 potential, in contrast, ranges from 'very low' to 'very high'. In Europe and Scotland high stewarding and transformative capacity are available, as risk-taking and uncertainty are embraced and innovation is embedded. However, the lack of engaged political culture tends to reduce the potential in all case studies. A U-turn towards

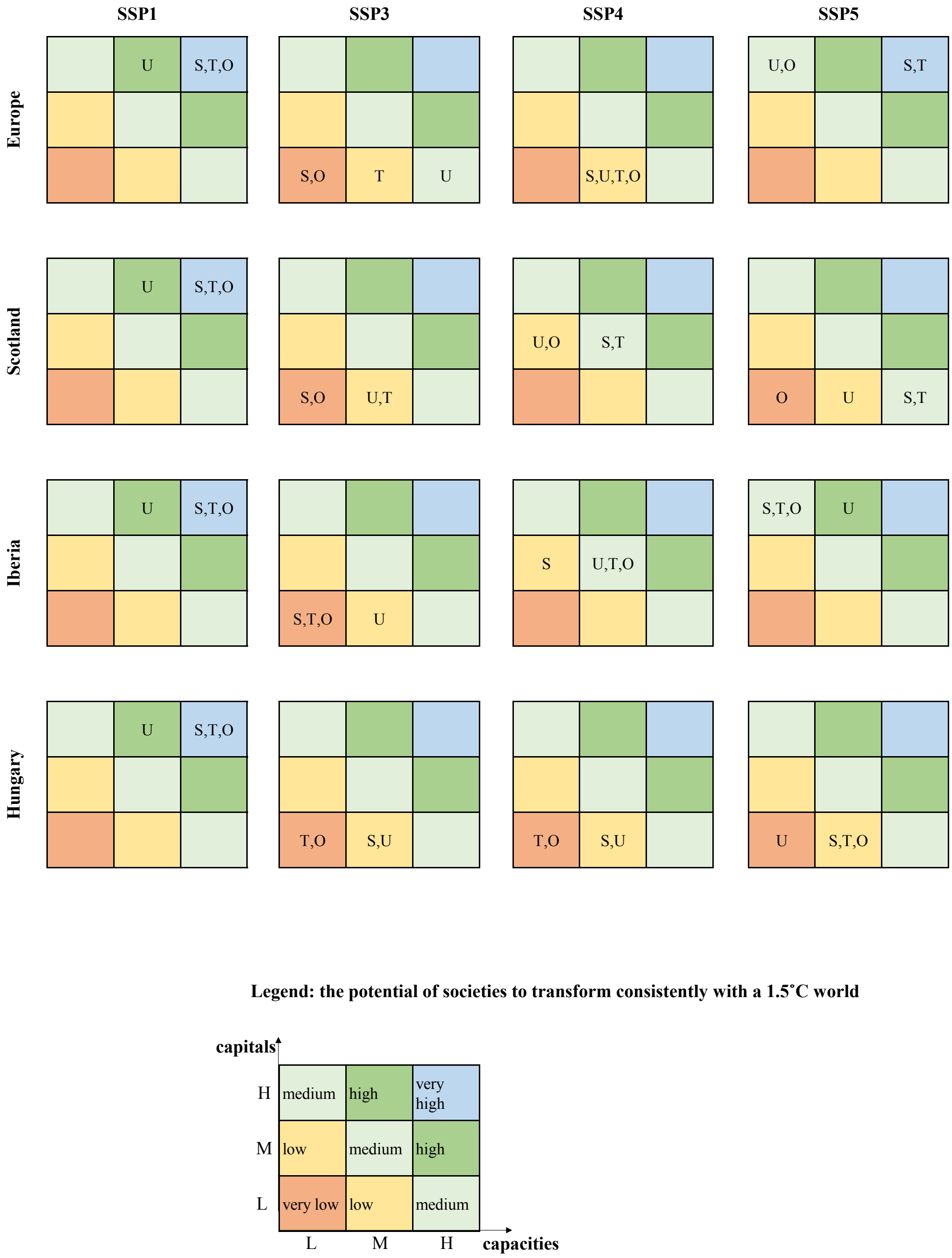

Figure 5.5: Analysis of the potential to transform society to function consistently with the requirements to achieve a 1.5 °C world for each SSP-RCP combination as a result of the combination of different levels of capitals and capacities in each case study in 2100. The capacities assessed are stewarding (S), unlocking (U), transformative (T) and orchestrating (O). Their position on the y axis depends on the combined level of human and social capital.

sustainability emerges in all SSP5 case studies by 2100, but this happens smoothly in Europe and Scotland whereas in Hungary and Iberia, with lower transformative potential, the transition is much more chaotic.

In summary, these results show important differences in the way in which capacities are manifested both between case studies and between SSPs. For example, in SSP5 (and to some extent in SSP4) transformative capacities enable large-scale deployment of high-tech solutions, whereas in SSP3 unlocking and orchestrating capacities can grow and enable low-technology community-based action and social innovation.

5.3.2 Potential application of the SSP capital and capacity framework to Integrated Assessment Modelling

The assessment of capitals and capacities for each scenario can complement the use of Integrated Assessment Models (IAMs). Our framework can provide a 'reality check' to indicate whether the societal conditions assumed within each SSP would actually allow the relevant actors to build and mobilise the capitals that are required to implement the mitigation options to meet a given RCP. In this section we link the level of capitals and capacities within each case study SSP (from Figures 5.4 and 5.5) to the mitigation and transformation options required to achieve the 1.5°C target (Figure 5.3), and consider the implications for IAM modelling.

For SSP1, all four case studies envisage that the level of social and human capital and the stewarding, transformative and orchestrating capacities increase to high levels by 2100, with the unlocking capacity starting high but falling to medium by 2100 as most citizens become satisfied with the status quo. The potential to implement all four types of mitigation (technological, institutional, lifestyle and land-use) is therefore generally high, if we assume that the high social and human capital will enable the high levels of manufactured and financial capital that are required for technological mitigation. Natural capital also increases in SSP1 (e.g. a large increase for Iberia and moderate increase for Hungary by 2100), indicating that land-based mitigation would also be viable, especially as there is a high level of stewarding and transformative capacity.

This can be compared with the mitigation actions required to reach RCP2.6 from the SSP1 baseline for the OECD region according to IAM modelling (Bauer et al., 2016, 2017; Popp et al., 2017; van Vuuren et al., 2017), bearing in mind that even stronger mitigation (beyond RCP2.6) will be required to reach the 1.5°C target. Mitigation in the SSP1-RCP2.6 IAM starts with a strong focus on reducing energy demand, through both technological and lifestyle measures. After 2040 there is a major shift from fossil fuel towards biomass and renewable energy, as well as extensive afforestation, which is made possible by the low demand for meat which frees up land for biomass and forests. This scenario thus involves rapid implementation of all four types of mitigation (technological, institutional, lifestyle and land-based), which in turn requires high levels of all four capacities. Our study complements the IAM modelling by giving confidence that the locally derived versions of SSP1 for Europe are broadly consistent with high levels of these capitals and capacities. For SSP3, in contrast, levels of social and human capital and orchestrating capacity decrease to low levels in all case studies as governance breaks down and anarchy prevails. Levels of the other capacities vary from low to medium across the case studies, with unlocking potential reaching a high level in the Eur-SSP by 2100 because of general dissatisfaction with the prevailing situation . This means that it is not possible to achieve a significant level of climate-change mitigation either through technological innovation (e.g. due to low transformative capacity) or land-use change (low stewarding capacity) consistent with the finding in the IAM literature that RCP 2.6 is not achievable with the global SSP3 (Riahi et al., 2017). However, this study shows that SSP3's turbulence may also enable dramatic (and, sometimes, enforced) behavioural and institutional changes with potential for local reconstruction when networks of people reorganise and effectively oppose the status-quo (when unlocking capacity is high). Similar potential has been identified in the POLFREE project, where low internationalisation and economic growth (as assumed in SSP3) have been linked to reduced GHGs emissions, increased circular economies and overall employment (Schanes et al., 2019; Jäger, 2016). For the unequal and divided society portrayed in SSP4, levels of social and human capital are low in the Eur-SSP and Hungary and medium in Scotland and Iberia. Transformative capacity is medium in Scotland and Iberia, indicating some potential for technological development including wind and solar power in Iberia. The other capacities are medium to low, indicating that it will be difficult to implement a comprehensive mitigation strategy that includes lifestyle change and land-based change. For comparison, the IAM modelling of SSP4 (Bauer et al., 2017; Calvin et al., 2017; Popp et al., 2017) requires very high investment in low-carbon energy technologies (nuclear, renewables and bioenergy with CCS) to reach RCP2.6, because the potential for land-based measures is limited by high population growth and high demand for food. This reliance on low-carbon energy supply results in a very expensive mitigation strategy, with carbon prices reaching over US\$2000/t CO_2 (compared to just US\$140/t CO_2 in SSP1 which focuses on demand reduction and land use). However, the low level of capitals and capacities in the locally derived SSPs raises doubts that this high level of technical investment and innovation could be achieved in practice. In addition, IAM modelling of SSP4 indicates that food prices would increase by a factor of six (Popp et al., 2017) due to pressure on land for bio-energy and afforestation. This would have implications for human and social capital that could further limit the mitigation potential. The locally derived fossil-fuel based SSP5 scenarios vary markedly between case studies. There could be a high potential for technological and land-based solutions in the Eur-SSP and Scotland to some extent, though in the other case studies and for other mitigation options the mitigation potential is limited by low capacities or capitals. The IAM modelling for SSP5 indicates that very drastic mitigation is needed to reach RCP2.6, to counter the strong growth in energy demand and lock-in to fossil fuel technologies up to 2040 (Bauer et al., 2017; Kriegler et al., 2017; Popp et al., 2017). By 2100, 65% of global final energy demand must be delivered as electricity and 7% as hydrogen, and fossil fuels are almost completely replaced by renewables, biomass with CCS (to provide negative emissions), and nuclear. Biomass demand in 2100 is the highest of all the scenarios, though a high biomass production efficiency is assumed, limiting the global cropland area to slightly less than in SSP4. As for SSP3, the uneven spread of capitals and capacities highlights potential difficulties with reaching this level of mitigation in practice. The Eur-SSP does provide the required high levels of capital and capacity for technological and land-based mitigation, but the local SSPs reveal limitations in capitals (Scotland), capacities (Iberia) or both (Hungary).

5.4 Discussion

The analysis of capitals and capacities within the locally derived European scenarios appears to reinforce the ability of SSP1 to deliver mitigation to at least RCP2.6, and confirms the finding that SSP3 is unlikely to be able to meet RCP2.6, unless the turbulence in the scenario leads to major institutional and lifestyle changes. For SSP4 and SSP5, which rely mainly on technological and land-based mitigation, the analysis raises doubts over the ability of society to deliver the level of mitigation required to achieve RCP2.6, given the relatively weak and uneven levels of human and social capital and governance capacity. To meet the 1.5°C target, even higher levels of mitigation would be required, which emphasises that only SSP1 might have a good chance of meeting this target. It is worth noting that the IAM modelling of the global SSP-RCP scenarios reported in Riahi et al. (2017) is intended as a reference case on which further analysis of climate impacts and adaptation can be built, and therefore does not consider the feedback effects of climate change on socio-economic systems (e.g. via impacts on ecosystems, energy systems, infrastructure or health). Given that some level of warming is implicit in all scenarios, even those which eventually achieve a RCP2.6 or 1.5°C target (possibly after overshoot), these potential negative feedbacks are significant. Consideration of the capitals and capacities framework helps to illustrate that climate change could negatively affect all five types of capital, which could further reduce the chances of reaching climate targets. The SSP1 scenario, which acts early and strongly to limit climate change and does not rely on overshoot followed by negative emissions, is likely to minimise these negative climate feedback effects and maximise the chances of successful mitigation. The choice of mitigation action could also create positive or negative feedbacks on capacity, as with the example of high food prices for SSP4 reported in Popp et al. (2017). Again, SSP1 with its focus on reduced demand for resources minimises this type of impact. Similarly, high levels of capital and capacity will foster more effective adaptation to climate impacts, which in turn will reduce the damage from climate change. The four ‘mitigation types’ used in our framework are derived from macro-scale mitigation studies. In local SSPs, the boundaries between those types become more blurred. In future assessments, the categories need to be explicitly assessed to capture the full potential of SSPs. For example, the results of SSP5 show that, in spite of lower potential for institutional and lifestyle change, there could be potential for actors to move towards the goal in ways that are (1) not covered by the categories or (2) fall between the categories. It is therefore necessary to inform global assessments with results from continental and local case studies and increase the relevance of mitigation at multiple levels. In the theoretical framework we have assumed that the capacities of actors to mobilise capitals can explain the potential to achieve the 1.5°C target. The results have shown that using the combined capitals-capacities framework allowed us to systematically identify the enabling and disabling conditions in the scenarios. This results in further enriching the understanding of the scenarios, with the capitals-capacities framework acting as the bridging framework between scenarios and policy. However, there was some mismatch between the results in Figures 5.4 and 5.5 and our framework of capacities (Figure 5.1) even though these categories were derived from a review of state-of-the-art literature on sustainability science. The main mismatch was the stewarding capacity in SSP1 and SSP5. With low challenges to adaptation and mitigation, SSP1 implies some level of transformation towards the 1.5°C target. However the stewarding capacity inferred from analysis of the stakeholder-derived scenario did not fit perfectly in either the 'medium' or 'high' category in our framework (Table 5.1). This was due to the combination of both long-term integrated planning and learning, typical of high stewarding capacity with a tendency to need strong regulation and a risk-averse attitude typical of medium stewarding capacity found in all SSP1 narratives (except for Iberia SSP1). Similarly, in the SSP5 scenarios the risk-embracing society in Europe and Scotland was difficult to match with the profit-driven communities of interests. The mismatches between capacity categories and challenges to mitigation and adaptation assumptions behind the European SSPs can be explained by the uncertainty due to (1) the interpretative nature of the capacity categories and (2) the diverging worldviews and opinions on the social challenges to sustainability and the 1.5°C target. Although studies such as Rockström et al. (2017) suggest clear decadal steps to be undertaken at global level for the road to 1.5°C target, the sub-global level shows diverging opinions because different beliefs and stakes are accounted for in order to enable the (global) action. This study adds two novel dimensions to actor-based approaches, participatory and policy-relevant scenarios over the past few years (Klein & Juhola, 2014), and narratives-only approaches (Nilsson et al., 2017) and fully empirical studies that cannot be directly applicable in other geographical areas or sectors (Chaudhury et al., 2013; Vervoort et al., 2014). This shows the complementarity of combining qualitative but systematic capacity analysis with indicators of capitals. Because the approach is systematic, it can be applied and tested in other geographical areas and sectors to increase comparability, in spite of the inevitable interpretative nature of narratives. Because of its simplicity and inclusion of actor-based capacity analysis, the approach can appeal to decision-makers and practitioners (Klein & Juhola, 2014). The categories of capacities in Table 5.1 enable impact modellers to include qualitative and quantitative information about the SSP context, beyond GDP and population-based indicators.

5.5 Conclusions

Our study has developed a transferable method for assessing the capacity of society to achieve the societal transformation necessary to meet climate targets, which has been tested across a range of spatial scales in European case studies. The assessment of capitals and capacities in the SSPs has the potential to inform a more realistic assessment of the potential uptake and effectiveness of a range of mitigation options needed to achieve 1.5°C by taking account of the diverse scenario-specific constraints and enablers. By integrating social science and participatory approaches with climate and socio-economic scenario modelling outputs, this transdisciplinary method can explore important feedbacks on the capacity for transformation that cannot be included in techno-economic models.

The results at sub-global level have highlighted different potentials to achieve the 1.5°C target for the same SSP across different case study areas, not only due to scale effects, but also to the normativity of the SSPs and the different beliefs and stakes of local actors that must be taken into account in order to enable change at global scale. Even in the most archetypal SSP1 and SSP3 scenarios, the capacities to enable change result in multiple possibilities to act which may lead to trade-offs or give unexpected opportunities for transformation and mitigation, such as in SSP3. The case studies consistently show that the SSPs with least challenges to mitigation, SSP1 and SSP4, have very different potentials for transformation, with SSP1 high or very high potential whereas SSP4 is restricted to low or medium potential due to high levels of inequality. Likewise the two SSPs with highest challenges, SSP3 and SSP5 have different potentials, with SSP5 having the highest potential in those case study versions with higher capitals and lower social inequality.

This study highlights the critical role played by social and human capital, and also by societal capacity to steward natural resources, orchestrate positive change, unlock new behaviours and transform existing institutions. These capitals and capacities are essential to enable the rapid innovation, behavioural change and international co-ordination needed to achieve the 1.5°C goal. Consideration of future changes in capitals and capacities alongside IAM projections could help to inform policy-making and determine the actions and strategies needed to achieve ambitious climate targets.

Chapter 6

Synthesis: The importance of scenarios to understand climate-change science

6.1 Introduction

This thesis should be seen in the context of current understanding of climate change as a socio-environmental problem and related to challenges to achieving a sustainable and equitable future (IPCC, 2018). The overall research questions were developed to guide the operationalisation of the essence and definition (ontology) as well as knowledge paradigms (epistemology) of climate-change science through scenario analysis. The scenario analyses in Chapters 2 to 5, which build on the state-of-the-art multi-scale scenario typologies and methodologies identified in Chapter 1, have been concretised using (i) a fuzzy-set methodology (Chapter 2); (ii) combined pan-European urbanisation modelling with narratives (Chapter 3); (iii) archetype analysis (Chapter 4) and (iv) a capital-capacity framework (Chapter 5). In this synthesis, the general contribution of Chapters 2 to 5 is evaluated in section 6.2 using the criteria of credibility, legitimacy, consistency and salience as introduced in Chapter 1. The results of this evaluation, which are shared across SSPs, are elaborated in Section 6.3 by discussing the concept of consistency which has emerged from Section 6.2. A special focus is given to one of the scenarios, Fossil-fuelled Development SSP5, because of its different weights on credibility, legitimacy, consistency and salience compared to the other scenarios. The synthesis concludes with a recommendation to further develop truly cross-scale quantitative and qualitative scenarios, based on the findings of this thesis.

6.2 The ontology and epistemology evaluation of climate-change scenarios

6.2.1 Linking different types of knowledge: credibility

Chapter 2 addresses RQ1: 'How can different types of knowledge be linked in exploratory scenarios?'. This involves linking narratives (qualitative scenarios) and quantifications (quantitative scenarios) in an SAS approach and, thus, addresses the epistemological problem of linking different sources of knowledge and uncertainties. Specifically, RQ1 focuses on involving stakeholders in the process of estimating model variables. On the implications of what stakeholder-led scenario narratives and modeller-led scenario quantifications actually mean before being linked with the SAS approach. While SAS consists of an iteration between narratives and quantifications, current methodologies link them by 'simplifying' or 'translating' the narratives into model variables. Starting from the premise that participatory narratives and model input are intrinsically different, Chapter 2 has tested the hypothesis that narratives can be linked to models, without being simplified. Although full uncertainty analyses have not been performed here, the results published in Li et al. (2017), Harrison et al. (2018a) and Rohat (2018) have utilised quantifications derived using the fuzzy-set methodology described in Chapter 2.

The discussion of the results in Rohat (2018) specifically addresses the credibility issue by recognising that the projections (derived using the fuzzy-set methods) do represent the experts' quantitative views. However, he recognises that the accuracy of the projections remains unknown and that the results reflect the experts' worldviews.

From the findings in Chapter 2 and Rohat (2018)'s conclusions, I derive that the fuzzy-set methodology has enhanced the transparency of the link between stakeholder and experts worldviews, but that it has not addressed the issue of replicability of the results. This implies that a different group of experts and stakeholders could potentially yield different results. Nevertheless, this observation relates to the development of environmental assessments in general (and thus not only scenarios) and the inclusion of ad-hoc assumptions and subjective decisions in the quantitative knowledge-development process (van der Sluijs, 2002). Fuzzy sets and probabilistic methods have both been identified to address the problem regarding the inclusion of expert knowledge. Chapter 2 acknowledges that both are important and complementary, because they address two types of uncertainty, related to different thinking systems. These are probabilities and vagueness, mathematically expressed in probability density functions and membership functions. By using the fuzzy-set methodology to analyse stakeholder-led key quantifications, developed as part of scenario narratives, modellers can reduce the difficulty of interpreting stakeholder-led narratives and link directly to the probabilistic uncertainty model (Krueger et al., 2012).

It is worth noting that, unlike Chapter 2, Rohat (2018)'s quantifications were directly translated into scenarios, whereas Chapter 2 and Harrison et al. (2018a) and Li et al. (2017) utilised the fuzzy-set method within a full SAS environment. Within this implementation of fuzzy sets, Li et al. (2017) suggested reducing the number of variables quantified with fuzzy sets to ensure internally consistent narratives, reducing subjectivity and the replicability fallacy. Additionally, Chapter 2 and Kok et al. (2014) emphasise the importance of limiting the number of stakeholder-quantified variables to ensure the process is understandable and feasible within the timing and effort constraints of a participatory setting.

As credibility is defined as scientific adequacy, the scenarios need to entail "authoritative, believable, and trusted information" (Cash et al., 2002) for both stakeholders and experts. The fuzzy-set methodology contributes to credibility from both perspectives due to the direct participation in both narratives and the quantifications and transparency of the process. In light of the results discussed above, I emphasise that fuzzy sets need to link both narratives and quantifications within an SAS approach to ensure overall internal consistency. Within SAS, the fuzzy-set methodology strengthens and clarifies the link between narratives and quantifications by allowing stakeholders rather than modellers to quantify key scenario assumptions. This increases the credibility of the linked narratives and quantifications.

Such a conclusion raises the question whether the scenario community should 'upgrade' the role of narratives in SAS. Currently, narratives are considered essential for communication and creativity in the stakeholder process but they are are not considered consistent and credible as quantitative scenarios (Van Vliet, 2011). The criteria for qualifying narratives as internally consistent and credible are thus limited to their internal consistency as model input

6.2.2 Implications of matching top-down with bottom-up scenarios: legitimacy

Chapter 3 addresses RQ2: 'What are the implications of matching top-down model-led quantitative knowledge and bottom-up stakeholder-led qualitative knowledge in multi-scale exploratory scenarios?'. Only by analysing narratives with quantifications can scale- and context-dependency be better identified, through the integration of bottom-up information in downscaled scenarios. Importantly, this allows different worldviews to legitimise the final analysis. The results have highlighted differences and commonalities among local scale drivers. These possibly revert directions of key global and European scale drivers (such as GDP or population trends) that are used as boundary conditions to downscale or nest scenarios. Examples of contrasting trends and directions emerged in all scenarios. In regional versions of SSP1, environmentally friendly countryside was proposed as being preferable to current countryside depopulation in Europe, whereas the preference for compact city dwelling is a key assumption of European SSP1 (although this latter trend often manifests in the form of green urban development). Locally-produced organic food and nature protection were also likely to lead to Europe-wide land-use change. In the regional versions of SSP3, an increase in poverty acts as a pull towards city fringes and the countryside. In climate-friendly but unequal regional versions of SSP4, spatial planning and compact cities are not only the result of rural to urban mobility (as a result of increased poverty), but also of Europe-wide ghettofication. In regional versions of SSP5, resource overexploitation and detrimental impacts result in possible inconsistencies with global SSP5 IAM-modelled strong economic growth trends.

In answer to the RQ, the implications of matching top-down and bottom-up scenarios increase legitimacy (and credibility) but bring about fundamental differences between sets of scenarios that are difficult to deal with. These include the balance between global scenarios being usefully constraining but not overly prescriptive (O'Neill et al., 2011). Chapter 3 reinforces the initial finding from Chapter 2 that judging the credibility of narratives based solely on consistency with model input is a shortcoming of current SAS. The results demonstrated that the model input, generated from downscaling global

SSPs, partly mismatched with participatory-derived trends for population growth and urbanisation. While the modelling exercise showed that the effect of the input variables can become confused with scenario trends, local scale qualitative narratives demonstrated that stakeholders consider different processes and even weigh different variables to explain demographic trends.

The results question whether 'nested', top-down and quantitatively-driven multi-scale-scenarios yield relevant information, given the influence of assumptions developed at different scales in different scenarios and divergence with parts of the narratives, and whether this comes at the expenses of legitimacy. While there are clear advantages to downscaling scenarios, such as consistently capturing the diversity across scenarios, the complex relationship of downscaled drivers, scenario and model uncertainty make results much more complicated and less distinguishable, especially for policy communication. Therefore, rather than prioritising either downscaling or stakeholder-led trends, combining both to interpret model-led downscaled drivers can add different views about what drives the problem (and thus enhance legitimacy while having credible scenarios). In conclusion, the scenarios in Chapter 3 include different views and are, in principle, thus legitimate. However, it should be stressed that the analysis is still a 'nested' multi-scale scenario analysis, because scaling is still addressed using a hard-linking "nesting" approach (Absar & Preston, 2015). Therefore, pan-European modelling results are fully consistent with global assumptions (Zurek & Henrichs, 2007) on economic growth, fertility, mortality and migration. Stakeholder-led narratives are only soft-linked a posteriori to both results and assumptions, and thus not directly modelled. This is because, in line with state-of-the-art pan-European modelling (see e.g. Rohat et al. (2019)), the European scale modelling results were designed to be fully consistent with the global SSP quantifications at the expense of divergent beliefs and values, to ensure credibility of the quantifications. Implementing a soft-linked modelling approach at pan-European scale would imply raising the question about a possible trade-off between salience and credibility to yielding legitimate scenarios. Further linkage between credibility and legitimacy of the analysis, and the relative importance of bottom-up and downscaled top-down knowledge is also addressed in Chapter 4 by evaluating the consistency of the scenarios.

6.2.3 Archetyping scenarios to frame top-down and bottom-up scenarios: consistency

Considering that both top-down and bottom-up and quantitative and qualitative knowledge should be matched to develop credible, legitimate scenarios (RQ1 and RQ2), in RQ3 (Chapter 4) I addressed the question 'How does archetyping scenarios frame global top-down and local bottom-up scenario narratives?' to evaluate credibility and legitimacy together by examining the consistency criterion as a balance for the other criteria. Consistency is a key element of multi-scale scenarios and determines the rigidity of the link across scales (Biggs et al., 2007; Zurek & Henrichs, 2007). The concept of scenario archetype is therefore well suited for this evaluation given its definition in the literature as “scenario families which share similar scenario logic which, in turn, reflect on similar quantifications” (van Vuuren et al., 2012a; Hunt et al., 2012) and (Harrison et al., 2018b). However, archetypes have also raised questions about the meaning of terms such as ‘scenario logic’ or ‘similar’, which is analysed in Chapter 3.

The results suggest that divergences across scales, for the same SSP, also relate to different meanings for the same scenario driver. For example, stakeholders gave different interpretations of the implication of ‘inequality’ and ‘carbon intensity’. Unequal and dystopian SSP3 and SSP4 are locally more nuanced than low-inequality SSP1 and SSP5. Low ‘inequality’ in SSP1 implies strong state intervention, emphasis on family values and economic growth in the Central Asian and, partly, in the Scottish case studies, whereas inequality implies local actors’ empowerment in the other European SSP1. SSP5 low-inequality and economic growth drivers were associated with ‘individualism’ in all case studies. Additional assumptions include free markets and human development in Europe, Central Asia and Scotland (although with strong state intervention in the last case). The particular combination of individualism, economic growth and environmental degradation was also associated with a fragmented society and overall social and environmental degradation in Hungarian and Iberian case studies.

The scenario consistency has been evaluated in all scenarios using scenario archetypes based on the qualitative analysis of key drivers (STEEP). Archetypes are affected by both scales and worldviews. The results show, as in Chapter 3, that the level of consistency across scales also depends on the scenario. Overall, the results of Chapter 4 highlight, perhaps unsurprisingly, that longer narratives tend to be more complex and describe more nuanced worldviews. Short narratives tend to systematically depict one worldview – typically described as ‘utopia’, ‘dystopia’ or ‘business as usual’.

The narratives’ scales and main purpose affect the level of detail and consistency provided. For instance, global narratives are homogenous because they are developed to depict the scenario archetype and provide qualitative information for IAV (narratives’ objectives). Instead, the European, Central Asian and local European scenarios are developed to be legitimate and reflect the input of different stakeholder backgrounds, besides providing credible qualitative information for IAV. The degree to which scenario narratives diverge from their corresponding archetypes reinforces the conclusion in Chapter 2 that both narratives and quantifications should be fully utilised to develop consistent and comparable scenarios that are capable of capturing the specific, context-relevant characteristics (legitimacy and salience). The concept of archetype effectively embodies the intermediate role between the level of generalisation of global scenarios, aimed to be boundary conditions for local case studies, and the specific bottom-up knowledge developed in local case studies aimed to reflect diverse stakes (Figure 6.1).

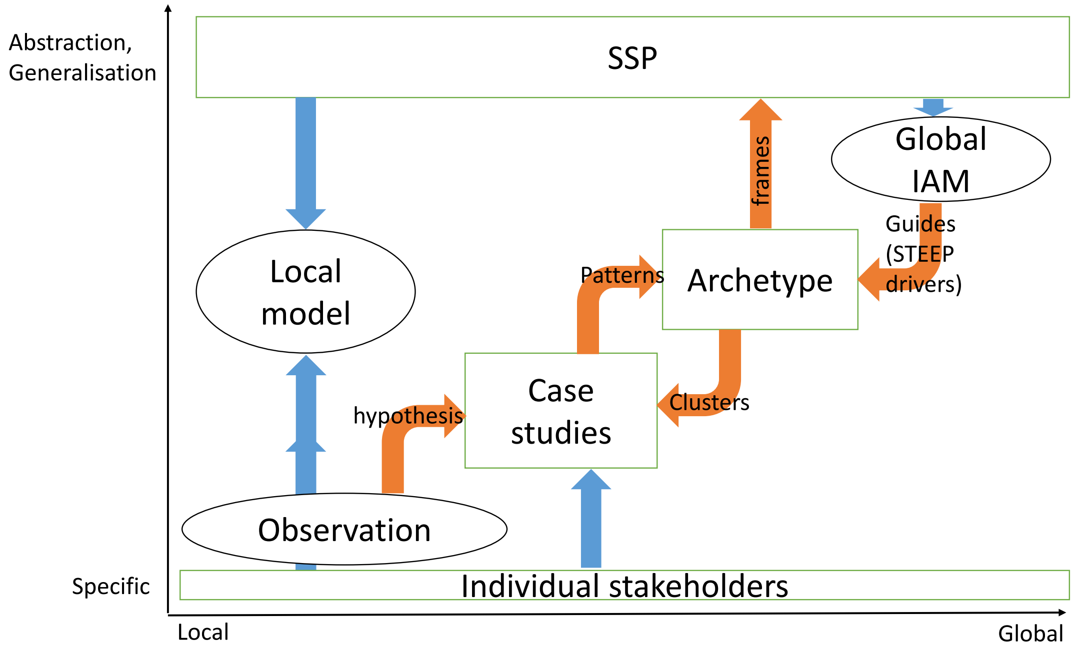

Figure 6.1: Role of archetypes in linking Shared Socio-economic Pathways (SSPs) and Integrated Assessment Model input at global scale (global IAM) with case studies and empirical approaches (local scale models, observations and stakeholder-led input). The blue arrows indicate the direction of input data and the orange arrows the conceptual linkages

Archetypes also guide the understanding of the different ways climate change is framed as an ontological problem. This, in turn, is affected by the different perceptions of what barriers and opportunities develop to challenge or support mitigation and adaptation strategies. The analysis was carried out ultimately to match the global IAM-perspective and the stakeholder-driven local worldviews. Its design reflects the current global community's framing of climate change as a driving force, along with the other STEEP drivers (in the form of SSP-RCP matrix) of challenges to adaptation and mitigation. Redefining climate change from an ontological point of view, as a problem of societal transformation rather than challenges to mitigation and adaptation, is addressed in subsection 6.2.4 with the analysis of scenario capitals and capacities.

In answer to the RQ, archetypes help framing and comparing scenarios developed at different scales by taking an intermediate position in the degree of specification. Archetypes were instrumental in identifying differences in worldviews and goals of different scenario sets.

6.2.4 Scenario relevance as potential to societal transformation: salience

In **Chapter 5** I address RQ4: 'What is the role of exploratory scenarios in improving understanding of the future potential to achieve desirable futures and address the challenges ahead?'. I start with the finding from Chapters 2 and 4 that both narratives and quantifications are needed to develop both credible and legitimate scenarios. If narratives are developed in close connection with quantifications, exploratory scenarios can be used not only to quantify impacts but also to assess potential in the scenarios to achieve a desirable future. The findings in Chapter 5 are based on the assumption that well-being and wealth indicators can combine both quantitative and qualitative information, such as capital s as semi-quantitative scenario drivers and the actors' capacities as part of scenario narratives.

The importance of analysing both capitals and capacities is emphasised by the emergent characteristics of European and regional SSPs. Even in the most archetypical SSP1 and SSP3 (see also Chapter 4), the capacities to enable change result in multiple possibilities to act, which can lead to unexpected trade-offs and opportunities. For example, SSP3 can result in unexpected opportunities emerging from unlocking and transformative capacities. Differences exist across case studies because of scales, beliefs and stakes of local actors. Additionally, actors in SSP5 have the broadest range potential across all case studies, depending on varying assumptions on inequality, capitals and environmental degradation.

In answer to the RQ, scenarios are salient because they improve understanding of the future potential to achieve desirable futures by analysing real-world capacities, embedded in the local scenario contexts, consistently across case studies. Consistency enhances rather than limits relevance because of the balance between top-down framing and specific information in the scenarios. In this form, the role of scenarios is not limited to exploring impacts (quantitatively); it also has the potential to effect future societal transformation, thus beyond the socio-economic model-led definition of climate change as challenge to adaptation and mitigation. Both Chapter 4 and Chapter 5 address the link between exploratory and normative scenarios and the meaning of the climate-change challenge.

6.3 Revisiting the concept of 'consistency'

6.3.1 Comparing SSPs across scales

In Section 6.2, I evaluate the definition of 'consistent scenarios' by expanding it to include the credibility, legitimacy and relevance criteria. The comparison across the SSPs demonstrates how the balance across the four criteria highlights different components when analysed together. For instance, credibility evaluates how 'scientifically sound', i.e. 'internally consistent' and 'plausible' (e.g Jiang (2014)) scenarios are. This also implies an element of 'trust' in the results (Kunseler et al., 2015) and 'trusting' the results also implies that users recognise the relevance or the legitimacy of the scenarios.

In such a broader interpretation, evaluating credibility, legitimacy, relevance and ultimately consistency for specific scenarios can be more complicated. While the archetype analysis in Chapter 4 demonstrates that some archetypes recur more frequently and tend to match, others tend to show a mismatch of scenarios across case studies for different reasons. The reasons can be attributed to different processes active at different scales (Chapter 3) and different worldviews on how the same attribute can be interpreted (Chapter 4), which affect the availability of capitals and capacities in each scenario (Chapter 5).

Another important factor may be the engagement process, as this could add an additional bias to the consistency of the scenarios (Gramberger et al., 2015; Kunseler et al., 2015). As the engagement process is not part of the analysis, and because the scenarios were all developed in similar processes across case studies, I treat all the scenarios of this analysis as comparable and focus on the analysis results rather than the development process.

Given these premises, the scenarios are compared in Figure 6.2 to represent key scenario drivers at the global scale, as represented in Jiang (2014), with the nested scenarios analysed here: Europe (EU), Central Asia (CA), Scotland, (SC), Iberia (IB), Hungary (HU). In addition to the overall global scenario logic, specific assumptions in the global SSPs have been tested against the literature and developed to be internally consistent. In this way, the correlations between GDP and education and GDP and urbanisation are positive (except for low/medium income countries in SSP4). Population and GDP/education/urbanisation are negatively and positively correlated in SSP1 and SSP4 and positive under SSP3 and SSP5 (high income countries) and negative in low-income countries for all SSPs except for SS4 (mixed trends) (Jiang, 2014).

As GDP and population trends for the sub-global SSPs were directly derived from the global SSPs, I compare these global trends to generic sub-global capitals utilised in this scenario analysis. I chose for human and social capitals because they tend to follow the same correlation to global variables, especially education and GDP (Dunford et al., 2015). From the analysis in Chapters 3 to 5 and the overview of Figure 6.2, SSP1 and SSP3 emerge as the most similar across case studies and global scenarios with either positive trends ('H') or negative trends ('L'). However SSP4 and, especially, SSP5 emerge as the most diverse, with opposing trends both within sub-global case studies and between global and sub-global case studies. Based on the state-of-the-art literature definitions that consistent scenarios across scales means scenarios sub-global scenarios need to fit

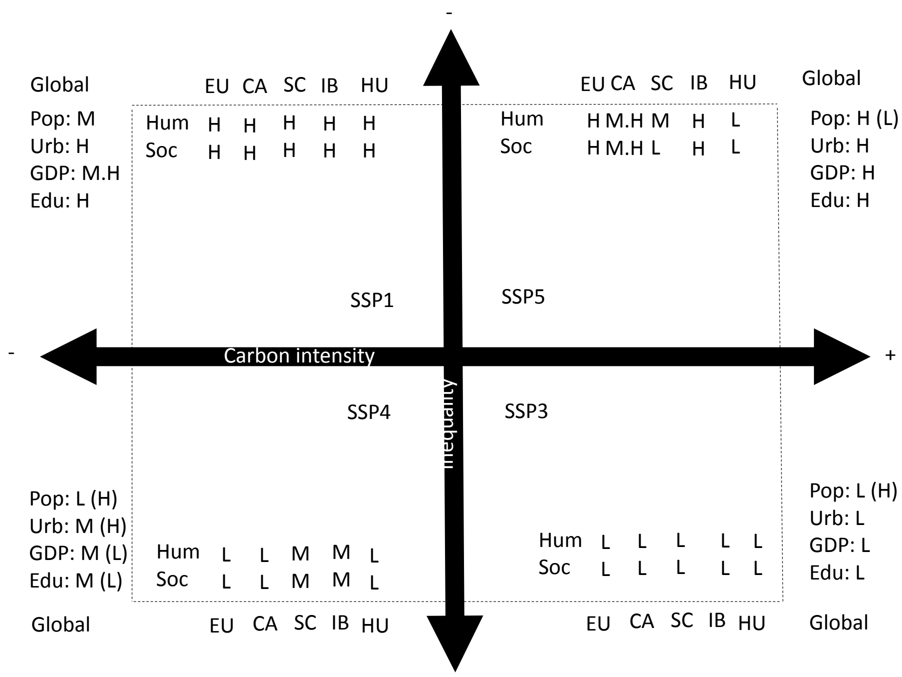

Figure 6.2: Comparing scenario trends (L=low, M=medium, H=high) of key socio-economic assumptions in global scenarios (population, GDP, urbanisation and education from Jiang (2014) and human and social capitals in European (EU), Central Asian (CA), Scottish (SC), Iberia (IB) and Hungarian (HU) scenarios in Chapter 5)

the global-scale scenario logic (Zurek & Henrichs, 2007), such SSP5 as analysed in this thesis should simply be dismissed as inconsistent. While the approach differs from Schweizer & Kurniawan (2016), in line with them I propose that such strict boundaries are unrealistic and undermine the relevance and legitimacy of the scenarios, and ultimately their credibility. As my analysis of the meaning of 'consistent scenarios' has been expanded to include the credibility, legitimacy and relevance criteria, I do not dismiss SSP5 across scales as 'inconsistent' (as would be the case in nested case studies), but rather utilise it as a concrete example of trade-offs and a way forward in both scenario analysis and climate-change science ontology and epistemology.

6.3.2 Is SSP5 consistent across scales?

In the global SSP uncertainty space of challenges to mitigation and adaptation, SSP5 presents high challenges to mitigation but low challenges to adaptation. The global scenario logic matches high human and social capital with energy-intensive economies and lifestyles, technological development and fast economic growth with low concern about environmental degradation. When presented with the SSP5 scenario logic, stakeholders in different case studies interpreted the narrative very differently. These differences are highlighted in both quantifications and narratives: **- Quantifications:** the assumptions of the global population projections reflect the current classifications of population growth as a function of economic growth and fertility. SSP5 is the only scenario with positive population growth (up to 47% in 2100) in Europe. Together with specific assumptions on urbanisation development such as, for example, high sprawl and suburban development, SSP5 has resulted – unsurprisingly – in the fastest urbanising scenario. However, for the ‘low fertility’ (Bulgaria, Croatia, Latvia, Lithuania, Malta and Romania) countries, such urbanisation does not happen. Stakeholder population and urbanisation assumptions partly matched: for example, stakeholders identified higher urbanisation as a result of changing lifestyles and ageing population. Current fertility trends were not considered at all in stakeholder-led population dynamics, while they were determinant in the geographical distribution of pan-European SSP5 urbanisation trends. On the contrary, stakeholders in the local case studies all identified mortality and, especially, migration as fundamental factors for future urbanisation trends. In other words, if urbanisation modelling were guided bottom-up, i.e. by stakeholder-led model input, SSP5 urbanisation drivers and results would have probably looked very different. **-Narratives:** the SSP5 narrative is very straightforward, at global scale, in that it fits previous scenarios (Kriegler et al., 2017) and the ‘market-first’ scenario archetype (Chapter 4). The cross-scale analysis, however, has demonstrated that not only some variables could diverge, but that key driving variables such as GDP and population trends can diverge as well. In the Scottish and European case studies, the trends were more consistent with the global STEEP drivers than in the Iberian and Hungarian case studies. For instance, the GDP growth and energy intensity drivers lead to lower inequality and high development of human and social capital in the European, Scottish and Central Asian scenarios, while the same drivers ultimately lead to collapsing socio-ecological systems, which in turn halted economic growth and, in the Iberian and Hungarian case study (in this latter case study, SSP5 ends with high mortality and increase in epidemics). Although the narratives vary greatly across case studies, stakeholders in all case studies emphasized the importance of the environment to sustain both societal and economic growth and deemed a ‘return’ to intensive energy lifestyle, focus on unconstrained economic growth and globalisation highly incompatible with low social inequality and high human and social capital. These considerations on SSP5 thus raise several questions:

1. Is such a ‘divergent’ scenario actually consistent across scales? SSP5 was developed using a similar stakeholder engagement process across all case studies, allowing stakeholders to diverge from the global archetype where they deemed necessary, so why is SSP5 more divergent than ‘utopian’ or ‘dystopian’ scenarios? For stakeholders, SSP5 contained elements of both ‘utopian’ and ‘dystopian’ scenarios. When matched with local conditions, qualitative drivers may change locally non-linearly and lead to a geographically diverse picture of the same scenario. Conversely, it is questionable whether ‘consistent’ narratives, across very diverse local conditions, are actually credible. This was the case, for example, of strong

outmigration in all case studies in the 'dystopia' SSP3 scenario need necessarily to assume that other hypothetical case studies find themselves in the opposite conditions (i.e. with strong immigration). Such linkages, across local scenarios, could be easily overlooked in the nested global-continental-national-local structure.

2. Are some of the key SSP5 assumptions obsolete in sub-global scales? The results suggest that truly cross-scale scenarios are hampered by the assumption that global scale scenarios provide *unquestioned* boundary conditions for multi-scale scenarios. More broadly, one of the IMPRESSIONS project's key findings is that solutions to high-end climate change ought to be radically 'transformative'. Additive 'adaptive' or 'mitigative' actions that can result in trade-offs (Tàbara et al. 2018) may not be sufficient to explore radical solutions to, for example, achieve the 1.5°C target (Chapter 5). These results imply that the overall architecture of the SSP-RCP-SPA could be aligned to represent the uncertainty space of challenges to societal transformation rather than challenges to mitigation and adaptation. The determination of key drivers should also be challenged, in view of the specific application of the SSP-RCP-SPA framework. For example, the inherent assumption that the GDP metric will relate to high human and social capital in the future as well, can be questionable as demonstrated by the local versions of SSP5.

The analysis of SSP5 has highlighted the importance of divergence in multi-scale scenarios, not only for specific context-bound drivers but also for others which are taken for granted in multi-scale scenario assessment, such as GDP or population trends. Such divergence possibly reflects different worldviews that challenge state-of-the-art knowledge and can ultimately question the role of global scenarios in guiding local scenarios versions with a nested approach. Ontologically, redefining the climate-change challenge as a sustainability challenge has helped frame the SSP uncertainty space as one of challenges to transformation, rather than challenges to mitigation and adaptation. Epistemologically, this challenge has implied the role of both narratives and quantifications to be equally important in capturing different uncertainties, stakes and worldviews.

6.3.3 Are consistent qualitative and quantitative scenarios desirable?

One clear advantage of developing multi-scale scenarios in with line the baseline SSP is the consistency of the quantifications, all coming from the same source. As a result, they are also better comparable across SSPs. However, some challenges may arise in future sub-global application of the baseline SSPs. This thesis has highlighted the following potential shortcomings of utilising the baseline SSPs:

1. **scale issue (Ch3)** globally, some SSPs cannot be linked to a certain RCP given their assumptions on land use, energy, etc. This is the case for SSP3 and RCP 8.5 and raises the question whether the global assumptions hold at sub-global scale, and

in particular at continental scale. This also relates to the problem of using the same data for the same set of scenarios, as this data needs to be scaled to the specific characteristics of the regions.

2. **qualitative-quantitative consistency (Ch2 and Ch4)** The overall consistency between narrative and quantification may be called into question when sub-global versions are developed, especially with participatory processes. As mentioned in the SSP4 marker publication by Calvin et al. 2016, stakeholders raise questions on how realistic such narratives are such as ‘how realistic is the continuation of the inequalities of SSP3 and SSP4, or the unconstrained emissions and GDP growth of SSP5?” Therefore, to yield relevant and credible scenarios, stakeholders generally re-define the scenario logic to make the narratives credible for the context. As a consequence, if local scenario narratives deviate excessively, SSP marker quantifications become inconsistent with the local narratives.

3. **exploratory vs normative (Ch5)** The baseline SSPs have led to the development of mitigation scenarios which explicitly incorporate the effect of climate change and mitigation policies. As the baseline SSPs are developed to be used in IAV (Riahi et al., 2017), the challenges to adaptation and mitigation, originally designed in the ‘basic SSP’ framework, are addressed separately.

More precisely, not all pathways available within SSP3 and SSP5 have been explored yet in the literature. Therefore, excluding *a priori* SSP3 and SSP5 combinations would limit the potential of SSPs and RCPs as exploratory scenarios. This thesis also urges scenario practitioners and users to carefully interpret scenario drivers and be aware that these do not necessarily contextualise the entire problem. This applies also to unquestioned drivers such as GDP, population and urbanisation. However, the design of the SSPs makes it problematic, as the scenarios have been designed to be further developed for sub-global analysis. Given the effective lack of bottom-up iteration, the globally developed databases for GDP, population and urbanisation do not necessarily account for locally relevant processes.

The sections above show that scenarios can have a different meaning depending on what they are treated ‘holistically’ or ‘reductively’. If scenarios consist of internally consistent variables, state-of-the-art methodologies such the linked-CIB approach (Schweizer & Kurniawan, 2016) and Morphological Analysis (Carlsen et al., 2016) exist to compute systematically internally consistent and diverse scenarios. The ‘intuitive method’ is based on developing narratives from a limited number of scenario drivers and was used to develop the scenarios analysed in this thesis. This method is less structured and may lead to less diverse scenarios than CIB or Morphological Analysis. However, it has the advantage of being established and facilitates discussion and comparison across scenarios in participatory settings.

Assuming the validity of utilising the ‘intuitive method’, this thesis has shown that it is possible to develop multi-scale scenarios according to well-established methodologies and yet that a dichotomy still exists in the link between qualitative and quantitative, between consistent and relevant scenarios and between exploratory and normative.

6.4 Conclusion

The European SSPs have been defined as a set of scenarios that should maximise credibility, legitimacy, consistency and salience in this synthesis. I have also discussed how reaching these criteria often entails trade-offs, especially in relation to the SSP5 example. With SSP5, the 'consistency' criteria needs to explicitly include both quantitative and qualitative aspects of the scenarios, in equal weight, to address all the other criteria.

The contribution of this thesis to the debate on the ontology of climate change is the recognition that scientific credibility is determined by the relevance to the real-world problems of both scientific approaches and findings. Climate change research has long focused on understanding the problem and quantifying likelihood of different emissions, rather than identifying robust solutions to adapt to climate change (Dessai & Hulme, 2004; Dessai et al., 2009). Given the worldwide emergence of sustainability and climate-change targets, the broader climate-change community acknowledges that the focus of climate change should be on win-win transformative solutions to avoid trade-offs between targets (Tàbara et al., 2018; IPCC, 2018).

From an epistemological perspective, relevance of scenario analysis to real-world problems can only be achieved if they are consistent, i.e. both scientifically credible and legitimate, in including multiple viewpoints. I addressed this by regarding narratives as a complement to quantified scenarios, without simplifying them. In line with Geels et al. 2016, I acknowledge different and complementary epistemologies in scenario analysis. True complementarity of both narratives and quantifications can address the oversimplification of global scenarios as non-realistic "mini-worlds" (Frame et al., 2018) and move towards cross-scale links to enhance scenario relevance to climate change.

The recently published Special Report on 1.5 °C (IPCC, 2018) emphasises that reducing future climate-related risks would require upscaling transformative action by identifying context-relevant capacity. Only by truly addressing societal needs at multiple scales can the urgent action needed to tackle climate change transform from one of the greatest challenges to one of the greatest opportunities of our time.

6.5 Beyond state-of-the-art: from multi-scale to cross-scale Shared Socio-economic Pathways

The seed for opportunity is given by exploiting the full potential of both scenario narratives and quantifications. While the importance of narratives has been recently re-instated (Kok et al., 2018; Schweizer & Kurniawan, 2016), its de facto role in recent extensions of the SSP framework is still too limited to communicative and creativity roles. This relates to the overarching epistemological questions on credibility and legitimacy: not only past trends and literature should inform key future scenario projections, but also novel insights from other sources of knowledge to better address the novel paradigm of demand-driven climate-change science (Lourenço et al., 2015).

More credible and legitimate scenarios are also more consistent and salient to address the ontological character of climate-change problems and solutions, also in the context of policy-relevant trade-offs with sustainability and equity. This is because consistency relates to scenarios which can balance credibility and legitimacy, without limiting either aspect.

As said, the contribution of this thesis is to emphasise these points. However, the operationalisation of consistent, truly cross-scale scenarios still needs to be addressed in the literature, although analyses are moving towards this direction e.g (Nilsson et al., 2017). A promising approach to developing a cross-scale scenario is further application of the archetype analysis to explore a wider range of uncertainty, beyond what is defined in the current understanding as 'plausible' or 'internally' consistent. This is because a diverse set of scenarios can enable more robust policies, but also contextualise transformative and emerging pathways to facilitate a normative vision (Carlsen et al., 2016).

References

Absar, S. M., & Preston, B. L. (2015). Extending the shared socioeconomic pathways for sub-national impacts, adaptation, and vulnerability studies. *Global Environmental Change*, *33*, 83–96. doi: http://dx.doi.org/10.1016/j.gloenvcha.2015.04.004.

Akimoto, K., Sano, F., & Tomoda, T. (2017). GHG emission pathways until 2300 for the 1.5 °c temperature rise target and the mitigation costs achieving the pathways. *Mitigation and Adaptation Strategies for Global Change*, *23*, 839–852. doi: https://doi.org/10.1007/s11027-017-9762-z.

Alcamo, J. (2008). The SAS approach: combining qualitative and quantitative knowledge in environmental scenarios. *Environmental futures: The practice of environmental scenario analysis*, *2*, 123–50.

Alcamo, J., & Henrichs, T. (2008). Towards guidelines for environmental scenario analysis. *Environmental futures: The practice of environmental scenario analysis*, (pp. 13–35).

Alcamo, J., Kok, K., Busch, G., Priess, J., Eickhout, B., Rounsevell, M., Rothman, D., & Heistermann, M. (2006). Searching for the future of land: Scenarios from the local to global scale. In E. Lambin, & H. Geist (Eds.), *Land-Use and Land-Cover Change* Global Change - The IGBP Series (pp. 137–155). Springer Berlin Heidelberg.

Alcamo, J., Vuuren, D., Ringler, C., Alder, J., Bennett, E., Lodge, D., Masui, T., Morita, T., Rosegrant, M., & Sala, O. (2005). Methodology for developing the ma scenarios. *Ecosystems and Human Well-being: Scenarios*, *2*, 145–172.

Allen, T., & Hoekstra, T. (1992). *Toward a Unified Ecology*. Columbia University Press.

Allen, T. F. H., & Starr, T. B. (1982). *Hierarchy Perspectives for Ecological Complexity /T.F.H. Allen and Thomas B. Starr*. University of Chicago Press,1982.

Avelino, F., & Wittmayer, J. M. (2016). Shifting power relations in sustainability transitions: A multi-actor perspective. *Journal of Environmental Policy & Planning*, *18*, 628–649. doi: 10.1080/1523908x.2015.1112259. Doi: 10.1080/1523908X.2015.1112259.

Bambergerl, M. (2000). Opportunities and challenges for integrating quantitative and qualitative research. *VF, itLE C vI-h*, (p. 3).

Banson, K. E., Nguyen, N. C., & Bosch, O. J. H. (2014). Using system archetypes to identify drivers and barriers for sustainable agriculture in africa: A case study in ghana. *Systems Research and Behavioral Science*, *33*, 79–99. doi: 10.1002/sres.2300.

Bauer, N. et al. (2017). Shared socio-economic pathways of the energy sector – quantifying the narratives. *Global Environmental Change*, *42*, 316–330. doi: https://doi.org/10.1016/j.gloenvcha.2016.07.006.

Bauer, N., Hilaire, J., Brecha, R. J., Edmonds, J., Jiang, K., Kriegler, E., Rogner, H.-H., & Sferra, F. (2016). Assessing global fossil fuel availability in a scenario framework. *Energy*, *111*, 580–592. doi: https://doi.org/10.1016/j.energy.2016.05.088.

Beumer, C., & Martens, P. (2010). Noah's ark or world wild web? cultural perspectives in global scenario studies and their function for biodiversity conservation in a changing world. *Sustainability*, *2*, 3211.

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. *Ecology and Society*, *12*, 17.

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures*, *38*, 723–739. doi: http://dx.doi.org/10.1016/j.futures.2005.12.002.

Boschetti, F., Price, J., & Walker, I. (2016). Myths of the future and scenario archetypes. *Technological Forecasting and Social Change*, *111*, 76–85. doi: https://doi.org/10.1016/j.techfore.2016.06.009.

Brown, C., Brown, E., Murray-Rust, D., Cojocaru, G., Savin, C., & Rounsevell, M. (2014). Analysing uncertainties in climate change impact assessment across sectors and scenarios. *Climatic Change*, (pp. 1–14).

Calvin, K. et al. (2017). The SSP4: A world of deepening inequality. *Global Environmental Change*, *42*, 284–296. doi: https://doi.org/10.1016/j.gloenvcha.2016.06.010.

Carlsen, H., Dreborg, K. H., & Wikman-Svahn, P. (2013). Tailor-made scenario planning for local adaptation to climate change. *Mitigation and Adaptation Strategies for Global Change*, *18*, 1239–1255. doi: 10.1007/s11027-012-9419-x.

Carlsen, H., Lempert, R., Wikman-Svahn, P., & Schweizer, V. (2016). Choosing small sets of policy-relevant scenarios by combining vulnerability and diversity approaches. *Environmental Modelling & Software*, *84*, 155–164. doi: https://doi.org/10.1016/j.envsoft.2016.06.011.

Carter, T. R., Fronzek, S., Inkinen, A., Lahtinen, I., Lahtinen, M., Mela, H., O'Brien, K. L., Rosentrater, L. D., Ruuhela, R., Simonsson, L., & Terama, E. (2016). Characterising vulnerability of the elderly to climate change in the nordic region. *Regional Environmental Change*, *16*, 43–58. doi: 10.1007/s10113-014-0688-7.

Cash, D., Clark, W., Alcock, F., Dickson, N., Eckley, N., & Jäger, J. (2002). *Salience,* *credibility, legitimacy and boundaries: linking research, assessment and decision making*. Cambridge: John F. Kennedy School of Government, Harvard University.

Cash, D. W., Adger, W. N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., & Young, O. (2006). Scale and cross-scale dynamics: governance and information in a multilevel world. *Ecology and society*, *11*, 8.

Chan, S., Falkner, R., Van Asselt, H., & Goldberg, M. (2015). Strengthening non-state climate action: a progress assessment of commitments launched at the 2014 un climate summit, .

Chapin, F. S., Carpenter, S. R., Kofinas, G. P., Folke, C., Abel, N., Clark, W. C., Olsson, P., Smith, D. M. S., Walker, B., & Young, O. R. (2010). Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends in ecology & evolution*, *25*, 241–249.

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. *Regional Environmental Change*, *13*, 389–398. doi: 10.1007/s10113-012-0350-1. Reg Environ Change.

Cornelissen, A. M. G., van den Berg, J., Koops, W. J., Grossman, M., & Udo, H. M. J. (2001). Assessment of the contribution of sustainability indicators to sustainable development: a novel approach using fuzzy set theory. *Agriculture, Ecosystems & Environment*, *86*, 173–185. doi: http://dx.doi.org/10.1016/S0167-8809(00)00272-3.

Corner, A., Markowitz, E., & Pidgeon, N. (2014). Public engagement with climate change: the role of human values. *Wiley Interdisciplinary Reviews: Climate Change*, *5*, 411–422. doi: 10.1002/wcc.269.

Cradock-Henry, N. A., Frame, B., Preston, B. L., Reisinger, A., & Rothman, D. S. (2018). Dynamic adaptive pathways in downscaled climate change scenarios. *Climatic Change*, . doi: 10.1007/s10584-018-2270-7.

Crutzen, P. J., & Stoermer, E. F. (2000). The "anthropocene". *IGBP Newsletter*, *41*, 17–18.

Dessai, S., & Hulme, M. (2004). Does climate adaptation policy need probabilities? *Climate Policy*, *4*, 107–128. doi: 10.1080/14693062.2004.9685515.

Dessai, S., Hulme, M., Lempert, R., & Pielke, R. (2009). Do we need better predictions to adapt to a changing climate? *Eos, Transactions American Geophysical Union*, *90*, 111–112. doi: 10.1029/2009eo130003.

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. *Climatic Change*, *128*, 339–354. doi: 10.1007/s10584-014-1162-8.

Dunn, M., Rounsevell, M. D., Carlsen, H., Dzebo, A., Lourenço, T. C., & Hagg, J. (2017).

To what extent are land resource managers preparing for high-end climate change in scotland? *Climatic Change*, *141*, 181–195. doi: 10.1007/s10584-016-1881-0.

Ebi, K. et al. (2014). A new scenario framework for climate change research: background, process, and future directions. *Climatic Change*, *122*, 363–372. doi: 10.1007/s10584-013-0912-3. Climatic Change.

Eisenack, K., Lüdeke, M., & Kropp, J. (2006). *Construction of archetypes as a formal method to analyze socialecological systems*. Technical Report, Paper presented at the Proceedings of the Institutional Dimensions of Global Environmental Change Synthesis Conference.

Feola, G. (2015). Societal transformation in response to global environmental change: A review of emerging concepts. *Ambio*, *44*, 376–390. doi: 10.1007/s13280-014-0582-z. 582[PII] 25431335[pmid] Ambio.

Ferrier, S. et al. (Eds.) (2016). *The methodological assessment report on scenarios and models of biodiversity and ecosystem services*. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

Field, C. B., Barros, V. R., Mach, K., & Mastrandrea, M. (2014). Climate change 2014: impacts, adaptation, and vulnerability. *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, .

Fischer, E. M., & Knutti, R. (2015). Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change*, *5*, 560–564. doi: 10.1038/nclimate2617.

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, *16*, 253 – 267. doi: https://doi.org/10.1016/j.gloenvcha.2006.04.002. Resilience, Vulnerability, and Adaptation: A Cross-Cutting Theme of the International Human Dimensions Programme on Global Environmental Change.

Fontaine, C. M., Rounsevell, M. D. A., & Barbette, A.-C. (2014). Locating household profiles in a polycentric region to refine the inputs to an agent-based model of residential mobility. *Environment and Planning B: Planning and Design*, *41*, 163–184. doi: 10.1068/b37072.

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. doi: 10.1016/j.crm.2018.05.001.

Frantzeskaki, N., Loorbach, D., & Meadowcroft, J. (2012). Governing societal transitions to sustainability. *International Journal of Sustainable Development*, *15*, 19–36.

Frantzeskaki, N., Wittmayer, J., & Loorbach, D. (2014). The role of partnerships in 'realising' urban sustainability in rotterdam's city ports area, the netherlands. *Journal* *of Cleaner Production*, *65*, 406–417.

Friedlingstein, P., Andrew, R. M., Rogelj, J., Peters, G. P., Canadell, J. G., Knutti, R., Luderer, G., Raupach, M. R., Schaeffer, M., van Vuuren, D. P., & Le Quere, C. (2014). Persistent growth of co2 emissions and implications for reaching climate targets. *Nature Geoscience*, *7*, 709–715. Review.

G20 (2009). Declaration of the leaders of the major economies forum on energy and climate. https://www.theguardian.com/environment/2009/jul/09/climate-change-g8. Draft of the communique that is due to be issued by world leaders at the Major Economies Forum.

Gallopín, G. C., Funtowicz, S., O'Connor, M., & Ravetz, J. (2001). Science for the twenty-first century: From social contract to the scientific core. *International Social Science Journal*, *53*, 219–229. doi: 10.1111/1468-2451.00311.

Geels, F. W. (2014). Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective. *Theory, Culture & Society*, *31*, 21–40.

Geels, F. W., Berkhout, F., & van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. *Nature Climate Change*, *6*, 576–583. doi: 10.1038/nclimate2980.

Gibson, C. C., Ostrom, E., & Ahn, T.-K. (2000). The concept of scale and the human dimensions of global change: a survey. *Ecological economics*, *32*, 217–239.

Giddens, A. (1979). *Central problems in social theory: Action, structure, and contradiction in social analysis* volume 241. Univ of California Press.

Gillard, R., Gouldson, A., Paavola, J., & Van Alstine, J. (2016). Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, *7*, 251–265.

Güneralp, B., & Seto, K. C. (2013). Futures of global urban expansion: uncertainties and implications for biodiversity conservation. *Environmental Research Letters*, *8*, 014025.

Gonçalves, J., Gomes, M. C., Ezequiel, S., Moreira, F., & Loupa-Ramos, I. (2017). Differentiating peri-urban areas: A transdisciplinary approach towards a typology. *Land Use Policy*, *63*, 331–341.

Gramberger, H. P. J. J. K. K. L. S. M. M. M. M. S. B., M., & Watson, M. (2013). *Report on the third CLIMSAVE European stakeholder workshop*. Report, . URL: `http://www.climsave.eu/climsave/outputs.html`.

Gramberger, M., Zellmer, K., Kok, K., & Metzger, M. (2015). Stakeholder integrated research (stir): a new approach tested in climate change adaptation research. *Climatic Change*, *128*, 201–214. doi: 10.1007/s10584-014-1225-x. Climatic Change.

Harrison, P., Holman, I., Cojocaru, G., Kok, K., Kontogianni, A., Metzger, M., & Gramberger, M. (2013). Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in europe. *Regional Environmental Change*, *13*, 761–780. doi: 10.1007/s10113-012-0361-y. Reg Environ Change.

Harrison, P. A., Dunford, R. W., Holman, I. P., Cojocaru, G., Madsen, M. S., Chen, P.-Y., Pedde, S., & Sandars, D. (2018a). Differences between low-end and high-end climate change impacts in europe across multiple sectors. *Regional Environmental Change*, . doi: 10.1007/s10113-018-1352-4.

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. *Climatic Change*, *128*, 153–167. doi: 10.1007/s10584-015-1324-3. Climatic Change.

Harrison, P. A., Z., H., Karabulut, A. A., ..., B. L., & Pedde, S. . (2018b). Synthesising plausible futures for biodiversity and ecosystem services in europe and central asia using scenario archetypes. *Ecology & Society (submitted)*, .

Hermwille, L. (2016). Climate change as a transformation challenge. a new climate policy paradigm? *GAIA-Ecological Perspectives for Science and Society*, *25*, 19–22.

Hodson, M., & Marvin, S. (2010). Can cities shape socio-technical transitions and how would we know if they were? *Research policy*, *39*, 477–485.

Hoekstra, A. Y. (2000). Appreciation of water: four perspectives. *Water policy*, *1*, 605–622.

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. *Regional Environmental Change*, *16*, 97–109. doi: 10.1007/s10113-014-0679-8.

Hölscher, F. N. L. D., K. (2018a). Transformative and orchestrating capacities in moving beyond experimentation in climate governance in rotterdam, the netherlands. In K. P. B. F. Turnheim, B. (Ed.), *Beyond experiments: Understanding how climate governance innovations become embedded*. Cambridge University Press.

Hölscher, K. (2018b). So what? transition management as a transformative approach to support governance capacities in cities. In H. K. B. M. Frantzeskaki, N., & F. Avelino (Eds.), *Co-creating sustainable urban futures. A primer on applying transition management in cities*. Tokyo: Springer.

Hulme, M. (2016). 1.5 [deg]c and climate research after the paris agreement. *Nature Climate Change*, *6*, 222–224. Commentary.

Hulme, M., Mitchell, J., Ingram, W., Lowe, J., Johns, T., New, M., & Viner, D. (1999). Climate change scenarios for global impacts studies. *Global Environmental Change*, *9*, S3–S19. doi: 10.1016/s0959-3780(99)00015-1.

Hunt, D. V. L. et al. (2012). Scenario archetypes: Converging rather than diverging themes. *Sustainability*, *4*, 740.

IIASA (2013). Ssp database (version 0.93).

IPCC (2014). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* volume 3. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (2018). *Global warming of 1.5 [deg] C - Summary for Policymakers*. Technical Report, IPCC. Approved at the First Joint Session of Working Groups I, II and III of the IPCC and accepted by the 48th Session of the IPCC, Incheon, Republic of Korea, 6 October 2018. Subject to Copy Editing.

van Ittersum, M. K., Rabbinge, R., & van Latesteijn, H. C. (1998). Exploratory land use studies and their role in strategic policy making. *Agricultural Systems*, *58*, 309–330. doi: http://dx.doi.org/10.1016/S0308-521X(98)00033-X.

Jäger, J. (2016). Civil society leads - in short. Http://polfree.seri.at/civil-society-leads-in-short/.

Jäger, J., Rounsevell, M. D. A., Harrison, P. A., Omann, I., Dunford, R., Kammerlander, M., & Pataki, G. (2015). Assessing policy robustness of climate change adaptation measures across sectors and scenarios. *Climatic Change*, *128*, 395–407. doi: 10.1007/s10584-014-1240-y.

Jiang, L. (2014). Internal consistency of demographic assumptions in the shared socioeconomic pathways. *Population and Environment*, *35*, 261–285. doi: 10.1007/s11111-014-0206-3.

Jiang, L., & O'Neill, B. C. (2017). Global urbanization projections for the shared socioeconomic pathways. *Global Environmental Change*, *42*, 193–199. doi: https://doi.org/10.1016/j.gloenvcha.2015.03.008.

Jones, L., & Kok, K. (2014). *Scenarios for use in ROBIN (Deliverable 2.3.1.)*. Report, .

Kc, S., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, *42*, 181–192. doi: https://doi.org/10.1016/j.gloenvcha.2014.06.004.

Kebede, A. S. et al. (2015). Direct and indirect impacts of climate and socio-economic change in europe: a sensitivity analysis for key land- and water-based sectors. *Climatic Change*, *128*, 261–277. doi: 10.1007/s10584-014-1313-y. Climatic Change.

Kebede, A. S. et al. (2018). Applying the global rcp–ssp–spa scenario framework at subnational scale: A multi-scale and participatory scenario approach. *Science of The Total Environment*, *635*, 659 – 672. doi: https://doi.org/10.1016/j.scitotenv.2018.03.368.

Kemp-Benedict, E. (2012). Telling better stories: strengthening the story in story and simulation. *Environmental Research Letters*, *7*, 041004.

Kivimaa, P., & Kern, F. (2016). Creative destruction or mere niche support? innovation policy mixes for sustainability transitions. *Research Policy*, *45*, 205–217.

Klein, R. J. T., & Juhola, S. (2014). A framework for nordic actor-oriented climate adaptation research. *Environmental Science & Policy*, *40*, 101–115. doi: http://dx.doi.org/10.1016/j.envsci.2014.01.011.

Kok, K. (2009). The potential of fuzzy cognitive maps for semi-quantitative scenario development, with an example from brazil. *Global Environmental Change*, *19*, 122–133.

Kok, K., Biggs, R., & Zurek, M. (2007). Methods for developing multiscale participatory scenarios: insights from southern africa and europe. *Ecology and Society*, *13*, 8.

Kok, K., Bärlund, I., Flörke, M., Holman, I., Gramberger, M., Sendzimir, J., Stuch, B., & Zellmer, K. (2014). European participatory scenario development: strengthening the link between stories and models. *Climatic Change*, (pp. 1–14). doi: 10.1007/s10584-014-1143-y. Climatic Change.

Kok, K., & Pedde, S. (2016). Impressions socio-economic scenarios. *IMPRESSIONS project*, .

Kok, K., Pedde, S., Gramberger, M., Harrison, P. A., & Holman, I. P. (2018). New european socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. *Regional Environmental Change*, . doi: 10.1007/s10113-018-1400-0.

Kosko, B. (1986). Fuzzy cognitive maps. *International Journal of Man-Machine Studies*, *24*, 65–75. doi: http://dx.doi.org/10.1016/S0020-7373(86)80040-2.

Kriegler, E. et al. (2017). Fossil-fueled development (ssp5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, *42*, 297–315. doi: 10.1016/j.gloenvcha.2016.05.015.

Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K., Kram, T., Riahi, K., Winkler, H., & van Vuuren, D. (2014). A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change*, *122*, 401–414. doi: 10.1007/s10584-013-0971-5. Climatic 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. *Global Environmental Change*, *22*, 807–822. doi: 10.1016/j.gloenvcha.2012.05.005.

Krueger, T., Page, T., Hubacek, K., Smith, L., & Hiscock, K. (2012). The role of expert opinion in environmental modelling. *Environmental Modelling & Software*, *36*, 4–18. doi: 10.1016/j.envsoft.2012.01.011.

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. doi: 10.1016/j.futures.2014.10.006.

Lempert, R. (2013). Scenarios that illuminate vulnerabilities and robust responses. *Climatic Change*, *117*, 627–646. doi: 10.1007/s10584-012-0574-6.

Levers, C. et al. (2015). Archetypical patterns and trajectories of land systems in europe. *Regional Environmental Change*, *18*, 715–732. doi: 10.1007/s10113-015-0907-x.

Li, S., Juhász-Horváth, L., Pedde, S., Pintér, L., Rounsevell, M. D. A., & Harrison, P. A. (2017). Integrated modelling of urban spatial development under uncertain climate futures: A case study in hungary. *Environmental Modelling & Software*, *96*, 251–264. doi: https://doi.org/10.1016/j.envsoft.2017.07.005.

Linard, C., Gilbert, M., Snow, R. W., Noor, A. M., & Tatem, A. J. (2012). Population distribution, settlement patterns and accessibility across africa in 2010. *PLoS ONE*, *7*, e31743. doi: 10.1371/journal.pone.0031743.

Lourenço, T. C., Cruz, M. J., Dzebo, A., Carlsen, H., Dunn, M., Juhász-Horváth, L., & Pinter, L. (2018). Are european decision-makers preparing for high-end climate change? *Regional Environmental Change*, . doi: 10.1007/s10113-018-1362-2.

Lourenço, T. C., Swart, R., Goosen, H., & Street, R. (2015). The rise of demand-driven climate services. *Nature Climate Change*, *6*, 13–14. doi: 10.1038/nclimate2836.

Mallampalli, V. R., Mavrommati, G., Thompson, J., Duveneck, M., Meyer, S., Ligmann-Zielinska, A., Druschke, C. G., Hychka, K., Kenney, M. A., & Kok, K. (2016). Methods for translating narrative scenarios into quantitative assessments of land use change. *Environmental Modelling & Software*, *82*, 7–20.

Middelkoop, H., Van Asselt, M., Van'T Klooster, S. A., Van Deursen, W., Kwadijk, J. C., & Buiteveld, H. (2004). Perspectives on flood management in the rhine and meuse rivers. *River research and applications*, *20*, 327–342.

Mokhtar, A., & Aram, S. (2017). Systemic insights into agricultural groundwater management: case of firuzabad plain, iran. *Water Policy*, *19*, 867–885. doi: 10.2166/wp.2017.159.

Moss, R. H. et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*, 747–756. 10.1038/nature08823.

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. *Global Environmental Change*, *45*, 124–132. doi: http://dx.doi.org/10.1016/j.gloenvcha.2017.06.001.

Nilsson, K., Nielsen, T. S., Aalbers, C., Bell, S., Boitier, B., Chery, J. P., Fertner, C., Groschowski, M., Haase, D., Loibl, W. et al. (2014). Strategies for sustainable urban development and urban-rural linkages. *European Journal of Spatial Development*, (pp.

25–p).

Oberlack, C. et al. (2018). Archetype analysis in sustainability research: Common core, multiple nuances and motivations. *Ecology & Society (in review)*, .

Oberlack, C., Tejada, L., Messerli, P., Rist, S., & Giger, M. (2016). Sustainable livelihoods in the global land rush? archetypes of livelihood vulnerability and sustainability potentials. *Global Environmental Change*, *41*, 153–171. doi: 10.1016/j.gloenvcha.2016.10.001.

O'Brien, K. (2015). Political agency: The key to tackling climate change. *Science*, *350*, 1170–1171. doi: 10.1126/science.aad0267.

O'Brien, K. L. (2016). Climate change and social transformations: is it time for a quantum leap? *Wiley Interdisciplinary Reviews: Climate Change*, *7*, 618–626. doi: 10.1002/wcc.413.

O'Hagan, A., Buck, C. E., Daneshkhah, A., Eiser, J. R., Garthwaite, P. H., Jenkinson, D. J., Oakley, J. E., & Rakow, T. (2006). Fundamentals of probability and judgement. In *Uncertain Judgements: Eliciting Experts' Probabilities* (pp. 1–24). John Wiley & Sons, Ltd. doi: 10.1002/0470033312.ch1.

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. *Climatic Change*, *122*, 387–400. doi: 10.1007/s10584-013-0905-2. Climatic Change.

O'Neill, B. C., Carter, T. R., Ebi, K. L., Edmonds, J., Hallegatte, S., Kemp-Benedict, E., Kriegler, E., Mearns, L., Moss, R., Riahi, K., van Ruijven, B., & Van Vuuren, D. (2011). *Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research*. Technical Report, National Center for Atmospheric Research (NCAR).

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. *Global Environmental Change*, *42*, 169–180. doi: https://doi.org/10.1016/j.gloenvcha.2015.01.004.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., & Lowe, J. (2016). The scenario model intercomparison project (scenariomip) for cmip6. *Geoscientific Model Development*, *9*, 3461.

O'Riordan, T., & Jordan, A. (1999). Institutions, climate change and cultural theory: towards a common analytical framework. *Global Environmental Change*, *9*, 81–93.

Pahl-Wostl, C. (2008). Participation in building environmental scenarios. *Environmental futures: The practice of environmental scenario analysis*, (pp. 105–22).

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. *Global Environmental Change*, *45*, 227–242. doi: https://doi.org/10.1016/j.gloenvcha.2016.12.002.

Pedde, S., Clarke, E., Rounsevell, M., & Terama, E. (2018a). Analysing scenarios across scales to project population and urban land-use in europe to 2100. *Population & Environment (submitted)*, .

Pedde, S., Kok, K., Hölscher, K., Frantzeskaki, N., Holman, I. P., Dunford, R., & Jaeger, J. (2018b). Advancing the use of scenarios to understand the capacity to act towards achieving the 1.5 [deg] c target. *Global Environmental Change (under review)*, .

Pedde, S., Kok, K., Onigkeit, J., Brown, C., Holman, I., & Harrison, P. A. (2018c). Bridging uncertainty concepts across narratives and simulations in environmental scenarios. *Regional Environmental Change*, . doi: 10.1007/s10113-018-1338-2.

Pereira, L. M., Hichert, T., Hamann, M., Preiser, R., & Biggs, R. (2018). Using futures methods to create transformative spaces: visions of a good anthropocene in southern africa. *Ecology and Society*, *23*. doi: 10.5751/es-09907-230119.

Peterson, T. C., Connolley, W. M., & Fleck, J. (2008). The myth of the 1970s global cooling consensus. *Bulletin of the American Meteorological Society*, *89*, 1325–1338. doi: 10.1175/2008bams2370.1.

Philcox, N., Knowler, D., & Haider, W. (2010). Eliciting stakeholder preferences: An application of qualitative and quantitative methods to shrimp aquaculture in the indian sundarbans. *Ocean & Coastal Management*, *53*, 123–134.

Pilli-Sihvola, K., van Oort, B., Hanssen-Bauer, I., Ollikainen, M., Rummukainen, M., & Tuomenvirta, H. (2015). Communication and use of climate scenarios for climate change adaptation in finland, sweden and norway. *Local Environment*, *20*, 510–524. doi: 10.1080/13549839.2014.967757. Doi: 10.1080/13549839.2014.967757.

Popp, A. et al. (2017). Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, *42*, 331–345. doi: 10.1016/j.gloenvcha.2016.10.002.

Porritt, J. (2007). *Capitalism as if the World Matters*. Earthscan.

Price, J. C., Walker, I. A., & Boschetti, F. (2014). Measuring cultural values and beliefs about environment to identify their role in climate change responses. *Journal of Environmental Psychology*, *37*, 8–20.

Raskin, P. (2005). Global scenarios in historical perspective. *Ecosystems and human well-being*, (p. 35).

Rasmussen, L. B. (2005). The narrative aspect of scenario building - how story telling may give people a memory of the future. *AI & SOCIETY*, *19*, 229–249. doi: 10.1007/s00146-005-0337-2.

Regan, H. M., Colyvan, M., & Burgman, M. A. (2002). A taxonomy and treatment of uncertainty for ecology and conservation biology. *Ecological applications*, *12*, 618–628.

Reginster, I., & Rounsevell, M. (2006). Scenarios of future urban land use in europe. *Environment and Planning B: Planning and Design*, *33*, 619–636.

Reimann, L., Merkens, J.-L., & Vafeidis, A. T. (2017). Regionalized shared socioeconomic pathways: Narratives and spatial population projections for the mediterranean coastal zone. *Regional Environmental Change*, *18*, 235–245. doi: 10.1007/s10113-017-1189-2.

Riahi, K. et al. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. doi: https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N., & Schellnhuber, H. J. (2017). A roadmap for rapid decarbonization. *Science*, *355*, 1269–1271. doi: 10.1126/science.aah3443.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., & Meinshausen, M. (2016). Paris agreement climate proposals need a boost to keep warming well below 2 °c. *Nature*, *534*, 631–639. Perspectives.

Rogelj, J., Hare, B., Nabel, J., Macey, K., Schaeffer, M., Markmann, K., & Meinshausen, M. (2009). Halfway to Copenhagen, no way to 2 °C. *Nature Climate Change*, (pp. 81–83). 10.1038/climate.2009.57.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 [deg] c. *Nature Climate Change*, *5*, 519–527. doi: 10.1038/nclimate2572.

Rohat, G. (2018). Projecting drivers of human vulnerability under the shared socioeconomic pathways. *International Journal of Environmental Research and Public Health*, *15*, 554. doi: 10.3390/ijerph15030554.

Rohat, G., Flacke, J., Dosio, A., Pedde, S., Dao, H., & van Maarseveen, M. (2019). Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in europe. *Global and Planetary Change*, *172*, 45–59. doi: 10.1016/j.gloplacha.2018.09.013.

Rounsevell, M. D., Pedroli, B., Erb, K.-H., Gramberger, M., Busck, A. G., Haberl, H., Kristensen, S., Kuemmerle, T., Lavorel, S., & Lindner, M. (2012). Challenges for land system science. *Land use policy*, *29*, 899–910.

van Ruijven, B. et al. (2014). Enhancing the relevance of shared socioeconomic pathways for climate change impacts, adaptation and vulnerability research. *Climatic Change*, *122*, 481–494. doi: 10.1007/s10584-013-0931-0. Climatic Change.

de Ruiter, H., Macdiarmid, J. I., Matthews, R. B., Kastner, T., Lynd, L. R., & Smith, P. (2017). Total global agricultural land footprint associated with uk food supply 1986–2011. *Global Environmental Change*, *43*, 72–81. doi: https://doi.org/10.1016/j.gloenvcha.2017.01.007.

Schanes, K., Jäger, J., & Drummond, P. (2019). Three scenario narratives for a resource-efficient and low-carbon europe in 2050. *Ecological Economics*, *155*, 70–79. doi: 10.1016/j.ecolecon.2018.02.009.

Scholes, R. J., Reyers, B., Biggs, R., Spierenburg, M. J., & Duriappah, A. (2013). Multi-scale and cross-scale assessments of social–ecological systems and their ecosystem services. *Current Opinion in Environmental Sustainability*, *5*, 16–25. doi: https://doi.org/10.1016/j.cosust.2013.01.004.

Schröter, D., Cramer, W., Leemans, R., Prentice, C. I., Araújo, M. B., Arnell, N. W., Bondeau, A., Bugmann, H., Carter, T. R., Gracia, C. A. et al. (2005). Ecosystem service supply and vulnerability to global change in europe. *Science*, .

Schweizer, V., & O'Neill, B. (2014). Systematic construction of global socioeconomic pathways using internally consistent element combinations. *Climatic Change*, *122*, 431–445. doi: 10.1007/s10584-013-0908-z. Climatic Change.

Schweizer, V. J., & Kriegler, E. (2012). Improving environmental change research with systematic techniques for qualitative scenarios. *Environmental Research Letters*, *7*, 044011.

Schweizer, V. J., & Kurniawan, J. H. (2016). Systematically linking qualitative elements of scenarios across levels, scales, and sectors. *Environmental Modelling & Software*, *79*, 322–333. doi: https://doi.org/10.1016/j.envsoft.2015.12.014.

Sietz, D., Ordoñez, J. C., Kok, M. T. J., Janssen, P., Hilderink, H. B. M., Tittonell, P., & Dijk, H. V. (2017). Nested archetypes of vulnerability in african drylands: where lies potential for sustainable agricultural intensification? *Environmental Research Letters*, *12*, 095006. doi: 10.1088/1748-9326/aa768b.

Sleeter, B. M., Sohl, T. L., Bouchard, M. A., Reker, R. R., Soulard, C. E., Acevedo, W., Griffith, G. E., Sleeter, R. R., Auch, R. F., Sayler, K. L., Prisley, S., & Zhu, Z. (2012). Scenarios of land use and land cover change in the conterminous united states: Utilizing the special report on emission scenarios at ecoregional scales. *Global Environmental Change*, *22*, 896–914. doi: https://doi.org/10.1016/j.gloenvcha.2012.03.008.

van der Sluijs, J. P. (2002). A way out of the credibility crisis of models used in integrated environmental assessment. *Futures*, *34*, 133–146. doi: 10.1016/s0016-3287(01)00051-9.

Van der Sluijs, J. P. (2007). Uncertainty and precaution in environmental management: insights from the upem conference. *Environmental Modelling & Software*, *22*, 590–598.

Steffen, W., Sanderson, R., Tyson, P., äger, J., Matson, J., P.A., III, B. M., Oldfield, F., Richardson, K., Schellnhuber, H.-J., Turner, B., & Wasson, R. (2004). *Global Change and the Earth System: A Planet under Pressure*. Global Change - The IGBP Series.

Springer-Verlag. doi: 10.1007/b137870.

Tàbara, J. D., Cots, F., Pedde, S., Hölscher, K., Kok, K., Lobanova, A., Capela Lourenço, T., Frantzeskaki, N., & Etherington, J. (2018). Exploring institutional transformations to address high-end climate change in iberia. *Sustainability*, *10*, 161.

Tàbara, J. D., Jäger, J., Mangalagiu, D., & Grasso, M. (2018). Defining transformative climate science to address high-end climate change. *Regional Environmental Change*, . doi: 10.1007/s10113-018-1288-8.

Tàbara, J. D., Mangalagiu, D., Kupers, R., Jaeger, C. C., Mandel, A., & Paroussos, L. (2013). Transformative targets in sustainability policy making: the case of the 30% eu mitigation goal. *Journal of Environmental Planning and Management*, *56*, 1180–1191. doi: 10.1080/09640568.2012.716365. Doi: 10.1080/09640568.2012.716365.

Terama, E., Clarke, E., Carter, T. R., & Rounsevell, M. D. A. (2017a). Population-driven land use in europe: combining the shared socioeconomic pathways (ssps) and artificial surface development. In Springer (Ed.), *Cities and Climate Conference 2017*.

Terama, E., Clarke, E., Rounsevell, M. D. A., Fronzek, S., & Carter, T. R. (2017b). Modelling population structure in the context of urban land use change in europe. *Regional Environmental Change*, . doi: 10.1007/s10113-017-1194-5.

Thompson, M., Ellis, R., & Wildavsky, A. (1990). *Cultural theory*. Westview Press.

Tinch, R., Jäger, J., Omann, I., Harrison, P. A., Wesely, J., & Dunford, R. (2015). Applying a capitals framework to measuring coping and adaptive capacity in integrated assessment models. *Climatic Change*, *128*, 323–337. doi: 10.1007/s10584-014-1299-5.

Uusitalo, L., Lehikoinen, A., Helle, I., & Myrberg, K. (2015). An overview of methods to evaluate uncertainty of deterministic models in decision support. *Environmental Modelling & Software*, *63*, 24–31. doi: http://dx.doi.org/10.1016/j.envsoft.2014.09.017.

Van Asselt, M. B., & Rotmans, J. (2002). Uncertainty in integrated assessment modelling. *Climatic Change*, *54*, 75–105.

Van Notten, P. W. F., Rotmans, J., van Asselt, M. B. A., & Rothman, D. S. (2003). An updated scenario typology. *Futures*, *35*, 423–443. doi: http://dx.doi.org/10.1016/S0016-3287(02)00090-3.

Van Vliet, M. (2011). *Bridging Gaps in the Scenario World: Linking Stakeholders, Modellers and Decision Makers*. Wageningen University.

Vermeulen, S. J. et al. (2013). Addressing uncertainty in adaptation planning for agriculture. *Proceedings of the National Academy of Sciences*, *110*, 8357–8362. doi: 10.1073/pnas.1219441110.

Vervoort, J. M., Rutting, L., Kok, K., Hermans, F. L., Veldkamp, T., Bregt, A. K., & van Lammeren, R. (2012). Exploring dimensions, scales, and cross-scale dynamics from the perspectives of change agents in social–ecological systems. *Ecology and Society*, *17*.

Vervoort, J. M. et al. (2014). Challenges to scenario-guided adaptive action on food security under climate change. *Global Environmental Change*, *28*, 383–394. doi: http://dx.doi.org/10.1016/j.gloenvcha.2014.03.001.

van Vliet, M., Kok, K., & Veldkamp, T. (2010). Linking stakeholders and modellers in scenario studies: The use of fuzzy cognitive maps as a communication and learning tool. *Futures*, *42*, 1–14. doi: http://dx.doi.org/10.1016/j.futures.2009.08.005.

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software*, *25*, 1268–1281. doi: http://dx.doi.org/10.1016/j.envsoft.2010.03.007.

van Voorn, G., Verburg, R., Kunseler, E.-M., Vader, J., & Janssen, P. (2016). A checklist for model credibility, salience, and legitimacy to improve information transfer in environmental policy assessments. *Environmental Modelling & Software*, *83*, 224–236. doi: 10.1016/j.envsoft.2016.06.003.

van Vuuren, D., Kriegler, E., O'Neill, B., Ebi, K., Riahi, K., Carter, T., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., & Winkler, H. (2014). A new scenario framework for climate change research: scenario matrix architecture. *Climatic Change*, *122*, 373–386. doi: 10.1007/s10584-013-0906-1. Climatic Change.

van Vuuren, D. P., & Carter, T. R. (2014). Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. *Climatic change*, *122*, 415–429.

van Vuuren, D. P., Kok, M. T. J., Girod, B., Lucas, P. L., & de Vries, B. (2012a). Scenarios in global environmental assessments: Key characteristics and lessons for future use. *Global Environmental Change*, *22*, 884–895. doi: http://dx.doi.org/10.1016/j.gloenvcha.2012.06.001.

van Vuuren, D. P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakicenovic, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., Rose, S. K., & Arnell, N. (2012b). A proposal for a new scenario framework to support research and assessment in different climate research communities. *Global Environmental Change*, *22*, 21–35. doi: https://doi.org/10.1016/j.gloenvcha.2011.08.002.

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: Climate Change*, *1*, 393–404. doi: 10.1002/wcc.50.

van Vuuren, D. P. et al. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, *42*, 237–250. doi: https://doi.org/10.1016/j.gloenvcha.2016.05.008.

Wardropper, C. B., Gillon, S., Mase, A. S., McKinney, E. A., Carpenter, S. R., & Rissman, A. R. (2016). Local perspectives and global archetypes in scenario development. *Ecology and Society*, *21*. doi: 10.5751/es-08384-210212. 12.

Weingart, P., Engels, A., & Pansegrau, P. (2000). Risks of communication: discourses on climate change in science, politics, and the mass media. *Public Understanding of Science*, *9*, 261–283. doi: 10.1088/0963-6625/9/3/304.

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., & Sendzimir, J. (2011). Tipping toward sustainability: emerging pathways of transformation. *AMBIO: A Journal of the Human Environment*, *40*, 762–780.

Westley, F., Tjornbo, O., Schultz, L., Olsson, P., Folke, C., Crona, B., & Bodin, r. (2013). A theory of transformative agency in linked social-ecological systems. *Ecology and Society*, *18*.

Wise, R., Fazey, I., Smith, M. S., Park, S., Eakin, H., Garderen, E. A. V., & Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, *28*, 325–336. doi: 10.1016/j.gloenvcha.2013.12.002.

Wittgenstein-Centre (2015). Wittgenstein centre: Wittgenstein centre data explorer version 1.2.

Zadeh, L. A. (1975a). The concept of a linguistic variable and its application to approximate reasoning-iii. *Information Sciences*, *9*, 43–80. doi: http://dx.doi.org/10.1016/0020-0255(75)90017-1.

Zadeh, L. A. (1975b). The concept of a linguistic variable and its application to approximate reasoning—ii. *Information Sciences*, *8*, 301–357. doi: http://dx.doi.org/10.1016/0020-0255(75)90046-8.

Zurek, M. B., & Henrichs, T. (2007). Linking scenarios across geographical scales in international environmental assessments. *Technological Forecasting and Social Change*, *74*, 1282–1295.

van der Zwaan, B., Calvin, K. V., & Clarke, L. E. (2016). Climate mitigation in latin america: Implications for energy and land use: Preface to the special section on the findings of the climacap-lamp project. *Energy Economics*, (pp. Medium: ED; Size: p. 495–498). (Netherlands) (HIMS) [Univ. of Amsterdam, Amsterdam . Faculty of Science] (PNNL) (United States) [Pacific Northwest National Lab. , Richland, WA . Joint Global Change Research Inst.].

Curriculum Vitae

Simona Pedde was born on 6 July 1983 in Genova, Italy. Her desire for an international career and lifestyle developed since her youth when she attended the international 'Liceo' Deledda in Genova. It was difficult, at that time, to start studying abroad and being financially independent, therefore she worked a couple of years to eventually choose International and Diplomatic Sciences at the University in Genoa, just to fly and study in Brussels under the Erasmus programme in 2006, after the first year. That was the life-changing event, because since then Simona left Italy for good, flying back and forth from Brussels to finalise her Bachelor in 2009. Prof. Mantelli, supervised her BSc thesis on 'Paul Crutzen's Concept of Anthropocene'. During her BSc thesis and experience in Brussels she realised that she would want to pursue an academic career and take further her BSc knowledge on climate change with an interdisciplinary, natural-science based MSc. After gaining work experience and saving-up to continue studying, Simona left Belgium to nearby Netherlands a year after her BSc, to start her MSc 'Climate Studies' in 2010 in Wageningen. She finalised her MSc in 2012 with a thesis titled 'Scenarios of the lived experience in South America: a focus on hydrology'. She then worked as a junior researcher and education assistant with Prof. Kroeze and, from 2013, PE&RC until starting her PhD. Her research was funded by the FP7 IMPRESSIONS project to develop European scenarios from the IPCC-based global scenario framework under supervision of dr Kok and Prof. Leemans. Since 1st October 2018, Simona works at CEH (UK) as natural capital scientist to co-develop UK scenarios...and to experience once more working abroad.

Peer-reviewed journal publications

1. **Pedde, S.**, Kroeze, C., Mayorga, E., Seitzinger, S.P. (2017). Modeling sources of nutrients in rivers draining into the Bay of Bengal—a scenario analysis. *Regional Environmental Change*, 17, 2495-2506. doi: 10.1007/s10113-017-1176-7

2. **Pedde, S.**, Kok, K., Onigkeit, J., Brown, C., Holman, I., & Harrison, P.A. (2018). Bridging uncertainty concepts across narratives and simulations in environmental scenar-

ios. *Regional Environmental Change*, 1-12. doi: 10.1007/s10113-018-1338-2

3. **Pedde, S.**, Clarke, E., Rounsevell, M., Terama, E. (2018). Analysing scenarios across scales to project population and urban land-use in Europe to 2100. *Submitted to Population and Environment*

4. **Pedde, S.**, Kok, K., Hölscher, K, Oberlack, C., Harrison, P.A., Leemans, R. (2018). Archetyping Shared Socio-economic Pathways across scales: an application to Central Asia and European case studies. *under review in Ecology & Society*

5. **Pedde, S.**, Kok, K., Hölscher, K., Frantzeskaki, N., Holman, I., Dunford, R., Smith, A. & Jäger J. (2018). Advancing the use of scenarios to understand society's capacity to achieve the 1.5 degree target. *under review in Global Environmental Change*

6. Kok, K., **Pedde, S.**, Gramberger, M., Harrison, P.A., Holman, I.P (2018). New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. *Regional Environmental Change*, 1-12. doi: 10.1007/s10113-018-1400-0

7. Li, S., Juhász-Horváth, L., **Pedde, S.**, Pintér, L., Rounsevell, M.D.A., Harrison, P.A. (2017). Integrated modelling of urban spatial development under uncertain climate futures: a case study in Hungary. *Environmental Modelling & Software*, 251-264, doi: 10.1016/j.envsoft.2017.07.005

8. Rohat, G., Flacke, J., Dosio, A., **Pedde, S.**, Dao, H., van Maarseveen, M., (2018). Influence of changes in socio-economic and climatic conditions on future heat-related health challenges in Europe. *Global and planetary change*, 45-49, doi: 10.1016/j.gloplacha.2018.09.013

9. Harrison, P.A., Dunford, R.W., Holman, I.P., Cojocaru, G., Madsen, M.S., Chen, P.Y., **Pedde, S.**, Sandars, D. (2018). Differences between low-end and high-end climate change impacts in Europe across multiple sectors. *Regional Environmental Change,*, 1-15, doi: 10.1007/s10113-018-1352-4

10. Tàbara, J.D., Frantzeskaki, N., Hölscher, K., **Pedde, S.**, Kok, K., Lamperti, F., Christensen, J.H., Jäger, J., Berry, P. (2018). Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, 120-129, doi: 10.1016/j.cosust.2018.01.012

11. Tàbara, J.D., Cots, F., **Pedde, S.**, Hölscher, K., Kok, K., Lovanova, A., Lourenço, T.C., Frantzeskaki, N., Etherington, J. (2018). Exploring Institutional Transformations to Address High-End Climate Change in Iberia. *Sustainability*, doi: 10.3390/su10010161

12. Frantzeskaki, N., Hölscher, K., Holman, I.P., **Pedde, S.**, Jaeger, J., Kok, K., Harrison, P.A. (2018) Transition pathways to sustainability in greater than 2 °C climate futures of

Europe. *In Review in Regional Environmental Change*

13. Harrison, P.A., Harmácková, Z., Karabulut, A.A., Brotons, L., ... **Pedde, S.**,.. (2018). Synthesising plausible futures for biodiversity and ecosystem services in Europe and Central Asia using scenario archetypes. *Submitted to Ecology & Society*

14. Santos, F., Jacobs, S., Boeraeve, F., Brotons, L., ... , **Pedde, S.**, ... (2018). Integrating the future values of nature for reaching sustainability and biodiversity goals: in Europe and Central Asia. *To be submitted to Nature Sustainability.*

Peer-reviewed book chapter

Chapter 9: Capacities in high-end scenarios in Europe: a governance perspective Authors: **Pedde, S.**, Hölscher, K., Frantzeskaki, N., Kok, K. in Hölscher, K., and Fratzeskaki, N., eds: 'Transformative climate governance: From 'what' to 'who' and 'how' through governance capacities'

Chapter 8: A transition management approach to develop transition pathways under high-end scenarios Authors: Frantzeskaki, N., Hölscher, K., Jäger, J., **Pedde, S.**, Holman, I., Tabara, J.D, Kok, K., Harrison, P. in Hölscher, K., and Fratzeskaki, N., eds: 'Transformative climate governance: From 'what' to 'who' and 'how' through governance capacities'

Other scientific publications

Contributing author to Chapter 5 of the IPBES regional assessment of Europe and central Asia 'Current and Future Interactions between Nature and Society', IPBES (2018)

Contribution to several IMPRESSIONS Deliverables (at least 10)

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC
PRODUCTION ECOLOGY & RESOURCE CONSERVATION

Review of literature (4.5 ECTS)

- Literature research and presentation of theoretical backgrounds in conferences, project meetings and in classes

Writing of project proposal (4.5 ECTS)

- New methodology for developing and integrating multiscale socio-economic scenarios

Post-graduate courses (4.5 ECTS)

- Bayesian Statistics; PE&RC (2015)
- The Choice; PE&RC (2015)
- Basic Statistics; PE&RC (2015)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Regional Environmental Change: Methods to develop local scenarios (2017)
- Global Environmental Change: Extending global scenarios for vulnerability assessment (2018)

Competence strengthening / skills courses (2.9 ECTS)

- Data Management and Planning; PE&RC (2015)
- Communication with the media and general public; PE&RC (2015)

- Brain Training; PE&RC (2015)
- Techniques for Writing and Presenting a Scientific Paper; PE&RC (2016)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.8 ECTS)

- PE&RC PhD Weekend (2015)
- PE&RC Day (2014 and 2015)
- PE&RC PhD Carousel (2018)

Discussion groups / local seminars / other scientific meetings (7.1 ECTS)

- Organisation and hosting of a 2-day Workshop on "Socio-economic scenarios for Europe and Scotland for 2100". Presentation + coordination of workshop (together with co-promotor); WUR (2014-2015)
- Meetings for coordinating scenario developments with pathways to adaptation and mitigation; Europe (2015-2017)
- Participation to discussion group for the development of "visions" of sustainable development in Europe in 2100; online (2015)
- Presentation and discussion of scenario development and challenges to integrated assessement modellers during modelling meeting; Denmark (2015)
- Co-organisation and hosting of writeshop for IPBES assessment chapter on scenarios
- Coordination of scenario group to quantify SSP2 European scenario; Europe (2018)

International symposia, workshops and conferences (12 ECTS)

- ESEE; oral presentation; Leeds, UK (2015)
- ECCA; oral presentation + facilitation workshop session; Copenhagen, Denmark (2015)
- PLACARD workshop on Foresight; Invited presentation on scenarios as foresight tools; Vienna, Austria (2016)
- ECCA; oral presentation + organisation of scientific session + chair panel discussion in 2 sessions + co-organisation of project stand; Glasgow, UK (2017)
- Impacts World; oral presentation at session + poster; Potsdam, Germany (2017)
- Adaptation futures; oral presentation + co-organisation of project stand; Capetown, South Africa (2018)
- Presentations and co-facilitation at 16 IMPRESSIONS workshops; throughout Europe and Central Asia (2015-2018)

Lecturing / supervision of practical's / tutorials (5 ECTS)

- Tourism Geographies (TGE) – Physical Geography teaching, course re-design, fieldwork and introductory GIS practical (2015-2018)
- Practicals on scenarios, modelling (LAPSUS). Correcting and grading reports (2015-2017)

- Invited lecturer to teaching scenarios at Summer School on Biodiversity and Ecosystem Services in Lugano, Switzerland (2018)

Supervision of 1 MSc student

- Nidhi Raina: Defining vulnerabilities of water sector in Southern Europe (2016/2017)

This research received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under Grant Agreement Number 603416

Cover design by János Orbán and Linda Juhasz Horvath