Extending the Shared Socioeconomic Pathways for Sub-national Impacts, Adaptation, and Vulnerability Studies

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Abstract

The exploration of alternative socioeconomic futures is an important aspect of understanding the potential consequences of climate change. While socioeconomic scenarios are common and, at times essential, tools for the impact, adaptation and vulnerability and integrated assessment modeling research communities, their approaches to scenario development have historically been quite distinct. However, increasing convergence of impact, adaptation and vulnerability and integrated assessment modeling research in terms of scales of analysis suggests there may be value in the development of a common framework for socioeconomic scenarios. The Shared Socioeconomic Pathways represents an opportunity for the development of such a common framework. However, the scales at which these global storylines have been developed are largely incommensurate with the sub-national scales at which impact, adaptation and vulnerability, and increasingly integrated assessment modeling, studies are conducted. The objective of this study was to develop sub-national and sectoral extensions of the global SSP storylines in order to identify future socioeconomic challenges for adaptation for the U.S. Southeast. A set of nested qualitative socioeconomic storyline elements, integrated storylines, and accompanying quantitative indicators were developed through an application of the Factor-Actor-Sector framework. In addition to revealing challenges and opportunities associated with the use of the SSPs as a basis for more refined scenario development, this study generated sub-national storyline elements and storylines that can subsequently be used to explore the implications of alternative sub-national socioeconomic futures for the assessment of climate change impacts and adaptation.

Keywords: socioeconomic scenarios, Shared Socioeconomic Pathways, climate change, vulnerability, adaptive capacity

1. Introduction

The evolution of human systems is a key factor influencing societal vulnerability to climate variability and climate change (Denton and Wilbanks, 2014; IPCC, 2012). Future economic development pathways at global, national, sub-national, and local levels, for example, will influence future emissions of greenhouse gases (Denton and Wilbanks, 2014), the exposure of human populations to climate variability and change (IPCC, 2012; Preston, 2013), and society's adaptive and mitigative capacities to reduce climate risk (Adger, 2007). Therefore, prognostic studies of the potential consequences of climate change should account for the non-stationarity of human systems and the uncertainty of future development pathways if they are to generate insights that are both credible and relevant for problem orientation and risk management (Berkhout et al., 2013; Preston et al., 2011). As future development pathways, globally and locally, are subject to some degree of irreducible uncertainty, scenarios are one of the most common approaches to representing future socioeconomic conditions and trends within integrated assessment modeling (IAM) (Edmonds et al., 2012; Nakićenović and Swart, 2000; Valverde, 2004) and climate change impacts, adaptation and vulnerability (IAV) research (Amer et al., 2013; van Ruijven et al., 2013; Varum and Melo, 2010).

To date, the IAM and IAV research communities have adopted different approaches to the development and use of socioeconomic scenarios, due to differences in research scales and objectives. The IAV community often develops scenarios that focus on context-specific aspects of socioeconomic systems that are focused on particular geographies or sectors (Birkmann et al., 2013; Brand et al., 2013; Kok et al., 2007; van Ruijven et al., 2014; Vervoort et al., 2014). Furthermore, there is often an element of stakeholder participation in the scenario development process to capture the values, preferences, and concerns of those that would be affected by, and have responsiblity for responding to, climate change and its consequences. Such scenarios are often fit-for-purpose, but as such may have little connection to global socioeconomic processes, and they may not be readily comparable (van Ruijven et al., 2013). For IAMs, quantiative socioeconomic scenarios represent critical modeling inputs. Yet, those inputs have traditionally been provided at relatively large-scale global or regional aggregations (Nakićenović and Swart, 2000). Furthermore, stakeholder participation in scenario development for IAMs has not been a priority and IAMs have been criticized for not explicilty incorporating qualitative aspects of social systems that give rise to market imperfections, institutional and informational constraints, and delayed policy implementation (Adger et al., 2008; Chambwerak et al., 2014; Ebi and Yohe, 2013; Klein et al., 2014). Nevertheless, IAMs provide a mechanism for the internally consistent modeling of future socioeconomic dynamics across space and time, and the IAM research community is directly involved in model intercomparison for alternative socioeconomic futures (e.g., Riahi et al., 2015).

Current trends in both IAV and IAM research suggest that their historically distinct scales and objectives may be converging. Investments by the U.S. Department of Energy and its national laboratories have focused on the development of regional IAM frameworks (de Bremond et al., 2014; Kraucunas et al., 2014; Moss et al., 2013) that resolve the macroeconomic impacts of regional- (i.e., sub-national) scale climate impacts and policy responses while maintaing links to global-scale biophysical and economic processes (Thomson et al., 2014). Similar IAM frameworks in Europe have demonstrated the value of multi-scale integrated modeling that also incorporates stakeholder participation in scenario and model development (Harrison et al., 2013). Meanwhile, efforts such as the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Huber et al., 2014) and the Agricultural Model Intercomparsion Project (AgMIP) (Rosenzweig et al., 2014) are indicative of growing integration and collaboration within the IAV community toward consistent, multi-scaled impact modeling. Collectively, these developments are enhancing the capacity to, on one hand, incorporate the sub-national to local-scale context characteristically explored through IAV studies into IAMs, and, on the other hand, scale-up IAV methods and analyses to provide more comprehensive understanding and geographic coverage of potential impacts. This convergence between the IAM and IAV communities suggests there may be strategic advantages in the development and use of a common framework for socioeconomic scenarios.

The Shared Socioeconomic Pathways (SSPs), which, in conjunction with the Representative Concentration Pathways, comprise the parallel scenario process (Ebi et al., 2014; Kriegler et al., 2012; Moss et al., 2010; O'Neill et al., 2014b; O’Neill et al., 2012), represent an opportunity to develop such a common framework. The SSPs are a new framework for the generation of insights regarding the future implications of climate change that enables the integration of projections of future climate change from Earth system models, future socioeconomic conditions, and alternative climate policy assumptions (O'Neill et al., 2014b; O’Neill et al., 2012). The SSPs describe plausible alternative trends in the evolution of society and ecosystems over the course of the 21st century assuming no explicit policies to mitigate or adapt to climate change. As they were developed to reflect driving forces important to understanding climate outcomes, they do not include explicit assumptions about future emissions, or climate change impacts. In other words, they reflect key inputs that enable understanding of vulnerabilities that determine the magnitude and pattern of climate change risks, but those are derived from other analysis tools such as IAMs or climate impact models.

As with prior efforts to develop socioeconomic scenarios, such as SRES (Nakićenović and Swart, 2000), and the Global Environment Outlook (GEO) (UNEP, 2002, 2007), the SSPs have been explicitly designed for the global scale with the intent of subsequently developing sub-global and sectoral extensions to address specific research questions of interest to the IAM and/or IAV research communities (Birkmann et al., 2013; Ebi et al., 2014; O'Neill et al., 2014a; van Ruijven et al., 2013). Global, continental, or even national storylines and scenarios are often too coarse geographically to capture vulnerability and adaptive capacity, which are widely recognized as being place-based phenomenon that are strongly, but not exclusively, influenced by local context (Kriegler et al., 2012). Information on socioeconomic futures at the sub-national scale may therefore be considered more relevant for IAV research and more legitimate for stakeholders and practitioners(Birkmann et al., 2013). Yet, there may be advantages to having such information linked to conditions and trends at the global scale that represent a common set of shared assumptions. For example, while global storylines and quantitative scenarios were developed as part of the Millennium Ecosystem Assessment (MA) (Carpenter, 2005), a range of sub-national assessments were also conducted that included storylines generated by various methods with varying degrees of consistency with the global storylines (Lebel et al., 2005). Similarly, in order for the IAV community, in particular, to capitalize on the opportunities presented by the SSPs, methods are needed to bridge the scale disconnect between the global SSP storylines and the sub-national scales at which much of the socioeconomic conditions that influence vulnerability, impacts, and adaptive capacity are relevant (see also Vervoort et al., 2014).

Here, we describe a method for developing sub-national and sectoral SSP storyline extensions for the U.S. Southeast as part of an effort to undertake climate impact modeling for the region's agriculture, water, and energy sectors that reflects uncertainty in future adaptive capacity. We apply an existing framework for the iterative development of socioeconomic storylines that span multiple spatial scales in order to generate a series of sub-national SSP storylines and quantitative indicators for the U.S. Southeast (Kok et al., 2006a; Rotmans et al., 2000). In so doing, the objectives were to a) identify potential challenges associated with using the global SSPs for nested storyline development, b) explore a specific method for managing these challenges, and c) discuss subsequent applications in which such storylines can be operationalized in both qualitative and quantitative IAV studies.

2. Conceptual Framework for Nested Storyline Development

2.1. The Shared Socioeconomic Pathways

The Shared Socioeconomic Pathways (SSPs) are the next generation of socioeconomic storylines for climate change research and assessment, emerging from the parallel scenario process (Moss et al., 2010). The basic SSPs are a set of global qualitative storylines and allied quantitative scenarios framed around various combinations of socioeconomic conditions and trajectories that create challenges to greenhouse gas mitigation and/or climate adaptation (Figure 1) (Kriegler et al., 2012; O'Neill et al., 2014a, b; O'Neill et al., 2012). The SSP1 (Sustainability) storyline assumes a future global socioeconomic development trajectory characterized by substantial gains in sustainability. As such, there are relatively low challenges for both mitigation and adaptation. In contrast, SSP3 (Regional Rivalry) assumes a breakdown in international cooperation and globalization leading to high challenges for both mitigation and adaptation. SSP4 (Inequality) and SSP5 (Fossil-fueled Development) explore permutations where there are high challenges along just one dimension of mitigation or adaptation, while SSP2 (Middle of the Road), is largely a business-as-usual trajectory. The SSPs are formulated independent of any explicit climate change projections or mitigation and adaptation policies, but rather represent socioeconomic factors that, for any given policy objective, would make mitigation or adaptation more achievable or difficult. The basic SSPs therefore represent socioeconomic boundary conditions for key driving forces that can inform subsequent extensions of the SSP storylines to add sub-national and/or sectoral context as needed for particular research activities and/or stakeholder needs (Ebi, 2013; O'Neill et al., 2014a, b). However, the SSPs have emerged relatively recently, and the development of such extended storylines is in a nascent state. Hence, this study explores one approach to developing extended storylines in a manner that retains internal consistency across geographic scales.

2.2. Bridging Scales in Socioeconomic Scenario Development

Various methodologies appear in the literature for developing socioeconomic scenarios for IAV and IAM research. These reflect different epistemologies and have different strengths and weaknesses for specific applications and desired outcomes. Generally, the various methodologies can be framed as top down and bottom up approaches (Biggs et al., 2007; Holman et al., 2005; Kok et al., 2006a; Sleeter et al., 2012), which reflect different entry points for scenario development with respect to scale, audience, and use. Bottom up approaches may, for example, employ participatory scenario development techniques to generate qualitative storylines for the study domain of interest, (Birkmann et al., 2013; Kok et al., 2006a; Kok et al., 2006b), and then, if relevant, link those scenarios to conditions and trends at more global scales (Holman et al., 2005; Sleeter et al., 2012). Such approaches allow maximum flexibility for scenario authors as they are unconstrained by prior efforts. However, although such storylines potentially can be mapped back to global level scenarios based on common underlying themes, the ad hoc generation of multiple independent storylines may create significant challenges with respect to making comparisons across storylines or storyline groupings (Zurek and Henrichs, 2007). In contrast, top down approaches use, often global, scenarios as boundary conditions for more regionalized scenarios at other scales (Kok et al., 2006b), and are often accompanied by the quantification of key variables. Top down approaches are best suited to situations in which a priori global scenarios are considered a desirable starting point for scenario development at other scales. This would include situations in which there is already some legitimacy or process associated with a set of scenarios; where there is interest in exploring cross-scale interactions and teleconnections; or where one seeks to maintain consistent assumptions across multiple studies (Biggs et al., 2007). Generating scenarios at finer spatial scales can be achieved by either downscaling approaches, which are particularly relevant for generating higher resolution around quantitative scenario elements (e.g., GDP, population, land use) (van Vuuren et al., 2007; van Vuuren et al., 2010), or nesting approaches in which one seeks to develop qualitative storylines that provide increasingly rich socioeconomic context at increasingly regionalized scales (Kok et al., 2006b; Leadley et al., 2010). As nested qualitative storylines are not limited in terms of the scope of socioeconomic elements they contain, they enable one to describe a broad set of socioeconomic processes, conditions, and interactions that are relevant for representing societal vulnerability and adaptive capacity.

Given the relationship between sub-national development trajectories and global trajectories is uncertain, there are two idealized assumptions one can make. First, sub-national trajectories may evolve in concert with global trajectories. For example, rapid population growth at the global scale may be reflected at sub-national scales, although what constitutes rapid growth may vary between scales. Alternatively, sub-national trajectories may evolve independently of global trajectories, in which case sub-national development is unbounded by global development pathways. These two assumptions translate into two general approaches to developing nested storylines (Figure 2). The first assumption can be represented by a 'one-to-many' nesting in which the storyline at each scale is consistent with a multitude of storylines at other scales (Biggs et al., 2007; Zurek and Henrichs, 2007). The one-to-many approach is perhaps most faithful to future uncertainty given inevitable surprises. However, it results in unconstrained growth in potential storylines as one shifts from one scale to another. This can result in a) a suite of storylines too numerous to effectively manage or communicate as well as b) redundancy among storylines variants. The second assumption can be represented by a 'one-to-one' nesting of storylines in which each storyline at a given geographic scale manifests at the next lower scale as a single storyline with fully consistent assumptions on drivers and scenario logics as the higher scale scenarios, but with enhanced context (see also Zurek and Henrichs, 2007). The 'one-to-one' approach to nesting is more expedient, but this is achieved by artificially constraining the ways in which futures evolve across different scales. This may be particularly problematic in scenario development processes involving stakeholder participation, as it reduces the opportunities for stakeholders to shape the manner in which futures are explored (Biggs et al., 2007). Nevertheless the one-to-many approach allows the exploration of disparate futures provided the parent global scenarios themselves are disparate themselves. This one-to-one approach was therefore selected as a means of developing nested storylines for current study based on the SSPs.

3.3. The Factor-Actor-Sector Framework

The method used to develop nested socioeconomic storylines or storyline extensions, is called the Factor-Actor-Sector framework (Kok et al., 2006b). Within this framework, a sector represents a sub-component of a national or social system. An actor represents an individual or organization of individuals with the capacity to effect and/or influence change. A factor represents an aspect of a social or natural system around which there are broad policy issues of particular interest (Kok et al., 2006b). This framework was first used during the VISIONS project funded by the European Commission to develop a range of alternative scenarios for European sectors as guidance for setting mid-term and long-term strategies for sustainable development both at the European and sub-national scales (Rotmans et al., 2000). The Factor-Actor-Sector framework was selected for the current study for its ability to address the complexity of socioeconomic systems in a systematic and structured manner and to enable investigators to define a priori the relevant aspects of socioeconomic futures. For example, by design, the global SSPs are comprised of succinct descriptions on a wide range of factors in order to avoid overly-prescribing future socioeconomic conditions in ways that would limit their usefulness for diverse applications. However, as a consequence, the global SSP storylines lack descriptions of some elements that are often considered relevant to IAV research such as the status and trends of certain sectors and/or the roles of specific actors and governance networks. Explicit identification of these elements is an essential starting point for the Factor-Actor-Sector framework. By deconstructing socioeconomic pathways into these elements, the framework creates entry points for global SSP storyline elements while also enabling the exploration of other aspects of socioeconomic futures. In so doing, the Factor-Actor-Sector framework facilitates the development of internally consistent, multi-scaled storylines, as each element at a given scale can be generated in a manner that directly links to like elements at other scales (Kok et al., 2006b).

4. Storyline Development

4.1. Global Storyline Elements

The first step in developing the nested storylines was the articulation of a core set of factors, actors, and sectors (referred to here as storyline elements), that were relevant across multiple spatial scales and to the study context (Table 1; Figure 3). Because sufficient resources were not available in the current study to enable a robust, multi-scaled, participatory scenario development process, the identification of relevant storyline elements was achieved through literature review. For factors, this process was informed by elements described in the global SSP storylines as well as by examining the factors that are commonly incorporated in other scenario exercises or used as input in IAMs or integrated assessment more broadly (IIASA, 2012b; Kok et al., 2006a; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O'Neill et al., 2012; UNEP, 2007). This enabled consideration for qualitative elements of socioeconomic systems that pose challenges to adaptation that are not routinely represented explicilty in IAMs or other top down modeling and assessment methods. For example, although specific actors are often not articulated in scenarios or in IAM experiments, a small set of actors was identified that influence the governance of different resources (e.g., public versus private institutions). Sectors were defined based upon common inclusion in global assessments such as the IPCC Working Groups II and III, common outputs from integrated assessment models, or because they have been identified as having significant geopolitical implications. The above criteria also capture those sectors that were particularly relevant for future applications of the nested storylines in the U.S. Southeast, specifically, energy, water, and agriculture.

To implement the global Factor-Actor-Sector framework, the five global SSP qualitative storylines were mapped to the defined factors, actors, and sectors (Figure 3) (O'Neill et al., 2014b; O'Neill et al., 2012). The SSP narratives were reviewed and language from each that provided context at the global scale for any of the defined elements was extracted and recorded in a database. Hence, each element was associated with a brief description of condition or trend as defined by the global SSP narrative. As the set of defined factors, actors, and sectors was generally broader than that which is described by the global SSPs, several factors and, particularly, actors and sectors remained undefined. Because a concerted effort was made to preserve the global SSP storyline elements intact as they were originally prescribed, and because the ultimate interest was in sub-national scale context, no attempt was made to fill these gaps in the definition of specific factors, actors, or sectors.

4.2. National Storyline Elements

The first level of storyline nesting consisted of the development of national storyline elements based on the global elements (Figure 3). In order to constrain the number of scenarios for consideration and to focus the nesting of socioeconomic storylines around challenges for adaptation, this study used four of the five global SSPs storylines, excluding SSP4 (Inequality) (Figure 1). The remaining four storylines span the continuum of low (SSP1 and SSP5), medium (SSP2), and high (SSP 4) challenges to adaptation. Both SSP1 and SSP5 were examined because they achieve such low challenges for adaptation through diametrically opposed development pathways. As a result, the implications for some of the scenario elements in SSP5 (e.g., biodiversity/conservation) run counter to the overall narrative of low challenges for adaptation. Meanwhile, because SSP5 and SSP4 represent high challenges to mitigation, they can be consistently applied in conjunction with an RCP8.5 scenario to juxtapose differential challenges to adaptation under more pessimistic scenarios of climate change. While the social inequality under SSP4 represents a classic indicator of low adaptive capacity, its low challenges vis-à-vis mitigation suggest it is less consistent with RCP8.5. In addition, the plausibility of SSP4, where future challenges to mitigation are low, but actors experience difficulties in the pursuit of adaptation, would appear less plausible than the other SSP storylines, particularly for developed nations such as the United States. As the relevant factors, actors, and sectors changed when the analysis lens focused on the United States, some elements considered in the global SSP storylines were dropped and not explored further at other scales. For example, while the Millennium Development Goals represent a key development metric for developing nations, they have little direct relevance to future U.S. socioeconomic development pathways. In addition, while agriculture and forestry was included as an aggregate Sector in the definition of global SSP elements, it was separated into two components of agriculture and forestry for the national level factors. Those elements that were retained were subsequently defined for the U.S. in a manner consistent with tight coupling to the global SSP narratives.

This process posed two methodological challenges. First, a process was required for defining national level storyline elements that corresponded with the global elements, despite the fact that the global SSP narratives lack detailed information at the national scale (although some national level data for the variables of population, GDP, and urbanization were available through the SSP data base (IIASA, 2012a). Second, storyline elements that were not articulated in the global SSP narratives had to be defined. Rather than develop this content purely de novo, these challenges were addressed through a review of peer reviewed and grey literature to identify existing storylines, scenarios, and allied information regarding current and future trends in different factors, actors, and sectors (Figure 3; Table 2). When relevant storylines or scenarios were identified, these were categorized based on their consistency with the global SSP storyline elements. For example, factors associated with the SSP5 (Fossil-fueled Development) storyline reflect high rates of U.S. population growth and economic development, but those trends are coupled to modest rates of technological change, particularly in the energy sector. In developing national storylines, U.S. demographic scenarios (e.g., Bierwagen et al., 2010; Guarneri, 2009; IIASA, 2012a, b; O'Neill et al., 2014b; O’Neill et al., 2012; USCB, 2012a, b), economic scenarios (e.g., MGI, 2011; O'Neill et al., 2014b; O’Neill et al., 2012; UNEP, 2007; WEF, 2010), and technology scenarios (e.g., IEA, 2012; Mintzer et al., 2003; O'Neill et al., 2014b; O’Neill et al., 2012; RF and GBN, 2010; UNEP, 2007) were reviewed to identify scenarios for these elements that were consistent with the Fossil-fueled Development storyline.

In addition to maintaining vertical consistency in a single storyline element across scales, efforts were also made to maintain horizontal consistency among different elements within the same scale. Factors such as population, GDP, and technology will evolve over time in tandem. Similarly, the future evolution of different U.S. sectors will be dependent upon future trajectories of global and U.S. factors. Hence, the development of content for each storyline element required ongoing consistency checks with other elements. For example, SSP1 (Sustainability) characterizes future global society as one associated with rapid rates of technological change, which ultimately affects the evolution of specific sectors such as energy and agriculture. Therefore, in using existing national scenarios of the energy (e.g., EIA, 2012a, b; Mintzer et al., 2003; O'Neill et al., 2014b; USDOS, 2010) and agriculture (e.g., ERS, 2011; IFTF, 2011; UNEP, 2007) sectors to develop national storyline elements for different SSPs, content for SSP1 for these sectors was derived from those existing sectoral scenarios that suggested similarly rapid rates of technological change.

4.3. Sub-National Storyline Elements

For sub-national storylines, the factors and actors considered in storyline development remained the same as those for the national storylines, but for the sectors, the focus narrowed to elaborate storyline elements for the three sectors considered most relevant to the study focus: energy, water and agriculture (Table 1). As in the case of national storylines, the sub-national storyline elements were developed using national storylines and scenarios that contained sub-national detail as well as more state-based information (Table 2). Generally, identifying sources of information and scenarios regarding future factors, actors, and sectors at the sub-national scale was more challenging. As a consequence, the development of storyline elements was often based upon extrapolating the current socioeconomic context of the region while attempting to maintain vertical and horizontal consistency with other storyline elements.

Although sub-national storyline elements were largely based on qualitative information, some quantitative indicators were developed to better understand the relative trends, magnitudes and dynamics of key factors within the region. These quantitative indicators were developed for state population and GDP by spatially disaggregating the U.S. population (IIASA-WIC v9) and GDP (IIASA-GDP v9) projections within the International Institute for Applied Systems Analysis (IIASA) SSP database version 0.93 (IIASA, 2012a) to the state level using the Integrated Climate and Land Use Scenarios (ICLUS) sponsored by the U.S. Environmental Protection Agency (Bierwagen et al., 2010) and Bureau of Economic Analysis data (BEA, 2013), respectively. For population, the global SRES storylines associated with individual ICLUS scenarios were first paired with the global SSP storylines to identify SRES/SSP pairings that were generally consistent. Hence, SSP1, SSP2, SSP3, and SSP5 storylines were paired with the ICLUS SRES B1, Base case, A2, and A1 scenarios, respectively (see also Nakićenović and Swart, 2000). The ICLUS population scenarios were then used to calculate the proportion of future growth in total U.S. population attributable to each U.S. county and state in 10-year time steps from 2010 to 2100. These proportions were then used as scaling factors, which were applied to the population increases generated for the corresponding SSP population scenarios for the United States in IIASA's SSP database. For state GDP scenarios, the average percentage contribution of each state to national GDP growth for 15 recent years (1997–2011) was calculated from the U.S. Bureau of Economic Analysis data (BEA, 2013) and these percentages were then used to disaggregate IIASA's SSP 21st century national U.S. GDP scenarios to state level GDP estimates.

5. Results

The method applied here generated a number of outputs. First, development of storyline elements for factors, actors, and sectors at the global, national, and sub-national level across the four SSPs resulted in a database with details regarding each storyline element, which enables one to compare storyline elements across different SSP assumptions and scales (Figure 4). For example, comparing SSP1 and SSP5 storyline elements for the water sector at each scale illustrates the evolution of information as one shifts from the global to the sub-national scale as well as the similarities and differences between the different SSPs with respect to outcomes and the pathways by which those outcomes are realized (Figure 5). By design, the SSPs provide only cursory information on the water sector at the global scale, with both SSP1 and SSP5 indicating that access to safe drinking water is expanded. They emphasize slightly different mechanisms by which such achievements are realized (achievement of MDGs in SSP1 while SSP5 emphasizes large-scale infrastructure investments), but these mechanisms are not mutually exclusive. At the national scale, the issue of water is broadened beyond just drinking water availability. Both SSP1 and SSP5 emphasize integrated water management and efficiency measures, yet SSP5 suggests a greater intensity of water resource development to meet the high levels of population growth and economic development. At the sub-national level, such distinctions become more evident. While SSP1 highlights sustainable water management practices, efficiency, and equity, SSP5 focuses on increasing privatization and resource development in order to meet demand and drive water use toward its highest value. Hence, both storylines suggest a future of water sufficiency through development pathways that enable adaptation, in contrast with other storylines such as SSP3 where capacity in the water sector is lower. However, the implications of SSP1 and SSP5 for long-term sustainability are not equivalent, and these two storylines imply significant differences in patterns of investment, governance, and the culture of water.

The use of quantitative scenarios to explore the key driving forces of population and demography at the sub-national level provided additional context regarding the manner in which different socioeconomic pathways manifest in the U.S. Southeast. For example, population growth of states of the U.S. Southeast was projected to peak during the 21^{st} century in SSP1, SSP2, and SSP3, with that peak arriving by approximately 2030 for SSP3 and toward the end of the century in SSP1 and SSP2 (Figure 5). Much of the change in the population at the sub-national level is associated with Florida and Texas – the two states that have the largest populations at present and are projected to account for a significant fraction of future population growth. These two states also account for a significant fraction of U.S. and Southeast GDP. However, the 21st century temporal dynamics of GDP scenarios for a given SSP are similar across the states. For SSP1 and SSP2, there is steady, but modest and linear, growth in GDP over the 21^{st} century. Growth in GDP under SSP3 is more constrained and has largely plateaued by 2100. In contrast, GDP under SSP5 grows exponentially, reaching levels that are several-fold higher than those observed for other SSPs. These methods resulted in population and GDP scenarios for U.S. Southeast states that scale directly to the U.S. scenarios within the IIASA database, but with the sub-national distribution determined by more localized trends and dynamics. However, at the aggregate state level, where gradients between urban and rural landscapes are masked, these scenarios are dominated by the national SSP scenarios and the historical distribution of population and GDP among U.S. states. This implies some degree of path dependence in future rates of change.

The database of storyline elements is extensive and therefore difficult to use to rapidly compare and contrast elements associated with different SSPs and/or scales. As such, a synthesis was conducted that focused on identifying the implications of each storyline element regarding challenges for adaptation (Figure 6). Storyline elements could be seen as creating moderate or large opportunities for adaptation, moderate or large challenges for adaptation, or neutral. In addition, factors reflect not just status but also trajectories, and thus factors have dual characteristics of both a trajectory (i.e., growth versus decline) as well as challenges to adaptation (i.e., moderate versus large). For example, SSP1 is associated with enabling conditions that pave the way for reductions in greenhouse gas emissions. Hence, the trajectory of the factor of emissions indicates a decline at the sub-national scale, which is interpreted as an increase in adaptive capacity under the assumption that lower emissions reduce the magnitude of future climate change to which society must adapt. In contrast, SSP5 is associated with high emissions growth thus poses greater challenges for adaptation. The synthesis also enables the rapid comparison of the implications of different SSP storylines at different scales. The storyline elements of SSP3 generally have a negative influence on adaptation across most of the factor, actors, and sectors. In contrast, most elements are positive under SSP1. It is also important to note that the trajectories of factors have different implications for adaptation under different storylines. At the sub-national scale, both SSP1 and SSP2 are associated with moderate growth in GDP. This has a positive influence on adaptive capacity under SSP1, under the assumption that economic growth helps to enable social, economic, and technological transitions associated with more sustainable futures. In contrast, under SSP2, modest GDP growth in the absence of an emphasis on sustainable development is associated with higher adverse externalities that reduce the overall opportunities for adaptation.

In addition to the synthesis, the individual storyline elements at the sub-national scale were integrated to develop sub-national storylines that act as extensions of the global SSP storylines (Appendix). However, they do not capture all aspects of each storyline element and thus reflect a generalized vision for the region, but with a particular emphasis on the priority sectors of agriculture, water, and energy. In conjunction with the storyline element database and the storyline element synthesis, these sub-national storylines represent different tools for defining socioeconomic boundary conditions at the sub-national level for subsequent IAV applications. Nevertheless, the qualitative nature of the storyline elements and storylines allows some degree of flexibility for further modification or extension to suit specific needs.

6. Discussion

The global SSP storylines and the ongoing process to expand their relevance for diverse applications represent a new opportunity to routinize the consideration of future socioeconomic conditions and pathways in climate change research and assessment (van Ruijven et al., 2013). The development of extensions of the global SSPs for different regions and/or sectors is an inherent component of the SSP framework. However, in so doing, two challenges must be addressed: a) the scale discordance challenge associated with using the global SSPs at sub-global scales (Moser, 2000; van Ruijven et al., 2013; Zurek and Henrichs, 2007) and b) the information gap challenge created by the lack of detailed information on some factors, actors, or sectors that may be relevant for SSP extensions. As illustrated here, the Factor-Actor-Sector framework provides a structured process for addressing these challenges. The explicit articulation of factors, actors, and sectors allows one to prioritize key storyline elements and manage consistency checks among different elements and across different scales. It is also sufficiently flexible to enable the incorporation of a broad array of information sources to facilitate the development of sub-national and/or sectoral SSP extensions. For example, the current study mapped existing national and sub-national scenarios and storylines for different factors, actors, and sectors to the SSP pathways. In so doing, the resulting storyline elements were both consistent with the global SSPs as well as existing perspectives on future U.S. socioeconomic pathways. This approach of using literature review to facilitate the development of SSP extensions could, however, be readily accompanied by, or replaced with, participatory scenario processes where stakeholders drive the development of SSP extensions (Carlsen et al., 2012; Harrison et al., 2013; Kok et al., 2006a). Hence, the Factor-Actor-Sector framework represents a potentially useful vehicle for structuring alternative mechanisms for extending the global SSPs.

Nevertheless, the application of the Factor-Actor-Sector framework also revealed challenges associated with nesting qualitative storylines within the SSPs. First and foremost, there is the question of what constitutes consistency between or within scales with respect to storyline elements. Zurek and Henrichs (2007) define consistent scenarios as being comprised of common boundary conditions, assumptions, and drivers. In this context, the national and sub-national storyline extensions developed here meet the criteria for consistency due to their adherence to the SSP logic framework and their representation of the various driving forces reflected in the global SSP storylines. However, given the global SSP storylines were, by design, developed to accommodate a range of futures, a diverse array of national or sub-national storyline elements could be considered to be consistent with any given SSP (O'Neill et al., 2014b). Those elements that were developed in the current study are therefore just one possible realization, and thus the nested storylines do not explore all the possible ways in which a given global SSP could manifest at the national or sub-national level. A second related challenge is that nesting process relies heavily on normative judgments, even when guided by additional literature or stakeholder participation. Hence, it would be difficult for two parallel applications of the Factors-Actors-Sectors framework to generate exactly the same nested storylines, although variants of a given SSP storyline should be recognizable as such. This suggests there may be trade-offs between flexibility and reproducibility, despite both being desirable features of scenario development methods. In contrast, the implementation of the global SSP storylines in an IAM provides a process-based and reproducible mechanism for evaluating socioeconomic responses to alternative boundary conditions. A third challenge is that the qualitative sub-national SSP storyline extensions may be difficult to operationalize within quantitative IAM or IAV modeling frameworks. Further interpretation and translation may be required to generate additional quantitative indicators that can be used as model inputs. These various challenges reflect the need to carefully consider the appropriateness of the method for developing SSP extensions and the potential value in exploring alternative methods.

While the current study reports the development of nested storylines for the U.S. Southeast, those storylines are not an end in themselves. Rather, the intent is to use these storylines for representing alternative socioeconomic pathways in the modeling of climate change impacts on the region, and key sectors at the land, water, energy nexus. To this end, the storylines help frame the selection of opportunities and constraints associated with adaptation of these sectors, including technological innovation and management practices that can be parameterized in crop, water resources management, and energy system models. This leads, however, to an additional consideration in the development of SSP extensions, which is their integration with scenarios of future climate conditions to explore the joint implications of both climatic and socioeconomic change for impacts, adaptation, and vulnerability. The Scenario Matrix Architecture (SMA) is a key feature of the "parallel process" of scenario development in which socioeconomic storylines developed under the SSP framework are integrated with climate scenarios based on general circulation or regional climate models forced by the RCP scenarios (Ebi et al., 2014; Eom et al., 2013; Moss et al., 2010; van Ruijven et al., 2013; van Vuuren et al., 2014; van Vuuren et al., 2012). The issue of whether socioeconomic challenges to adaptation associated with a given SSP can truly be considered to exist independent of the rate and magnitude of climate change is an open question worthy of consideration and deliberation in the application of the SMA. For example, the conventional development pathway implied by SSP5 implies a greater likelihood of significant climate change and adverse impacts, which could pose a negative feedback on development, posing greater challenges for adaptation than are implied in SSP5. Meanwhile, the sustainable development pathway of SSP1 seems inconsistent with a world in which RCP8.5 also transpires. Hence, while the SMA provides some flexible conceptual guidance for the integration of SSPs with scenarios of climate change for the purposes of IAV research, additional work is needed to enable the operationalization of the SMA in ways that are internally consistent. Development of a suite of case studies that illustrate alternative ways in which the SMA can be implemented at multiple scales using a range of different climate and socioeconomic scenarios and storylines will be an important process in learning how the SSPs can be usefully applied by the IAV community.

7. Conclusions

The SSP framework for the development of socioeconomic storylines and scenarios represents a valuable opportunity for the consistent treatment of alternative assumptions regarding socioeconomic development and climate change within the climate change research community. Nevertheless, ongoing differences in information needs as well as research epistemologies associated with the Earth system modeling, IAM, and IAV communities suggest that each will need to be an active participant in determining ways by which it can effectively engage the parallel process and the emerging scenario frameworks. For the IAV community, the SSPs can provide a common scenario platform that still enables researchers and practitioners to develop place-based and/or sector-specific understanding of climate change consequences. Before this can happen, however, methods (or a portfolio of methods) must be developed that enable researchers and practitioners to effectively use the SSP framework across a range of geographic scales. The development of nested storylines using approaches such as the Factor-Actor-Sector framework is one approach to achieving this end. Nevertheless, as illustrated in this study, the development of nested storyline elements and storylines invariably involves normative judgments of researchers and/or stakeholders. Therefore, no two attempts at extending the SSPs for regional or sectoral applications are likely to be identical. Such conceptual flexibility helps to align scenario development processes to assessment goals, which can be highly varied. A key test of the SSPs may therefore be the extent to which they can be successfully applied in disparate contexts while still remaining generally recognizable. However, additional case studies (e.g., Vervoort et al., 2014) with other methods are needed to evaluate the conditions under which the SSPs are useful in bridging scales in socioeconomic boundary conditions as well as for integration into the SMA under the parallel process.

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Figure Captions

Figure 1. Logic framework for the shared socioeconomic pathways (see also Kriegler et al., 2012; O'Neill et al., 2014a, b; O'Neill et al., 2012; van Vuuren et al., 2014). The various illustrative SSP pathways (SSPs 1–5) occupy different positions within the socioeconomic uncertainty space defined by challenges for mitigation and challenges for adaptation.

Figure 2. Comparison of alternative approaches to the development of nested socioeconomic storylines. A) represents a one-to-one nesting approach, where each global storyline is consistent with a single storyline at sub-global scales. B) represents a one-to-many nesting approach, where each global storyline is consistent with a range of alternative storylines at other scales.

Figure 3. Illustration of SSP storyline nesting based on the Factors-Actor-Sector framework.

Figure 4. Comparison of the storyline elements for the water sector associated with SSP1 and SSP5 storylines. The element description for the global level is based on the global SSP storylines. Elements at the national and sub-national level were derived through application of the Factor-Actor-Sector framework and were informed by other information sources on sectoral trends and scenarios (Table 2).

Figure 5. Quantitative population and GDP scenarios for states in the U.S. Southeast based on four different global SSP boundary conditions. Population and GDP scenarios were derived by applying county-level scaling factors to national population and GDP estimates within the IIASA database (IIASA, 2012a). Population scaling factors were based on the proportion of total U.S. population change attributed to individual counties as indicated by the ICLUS population scenarios (2010-2100). GDP scaling factors were based on the historical (1997-2011) average proportion of U.S. GDP attributed to the states considered in the current study.

Figure 6. Synthesis of the status and projected trends of factors, actors, and sectors considered in the current study with respect to their implications for adaptive capacity across multiple scales.

Table 1. Factors, Actors, and Sectors for global, national and sub-national storyline development.

	Global	Global	National	Sub-National
Factors	Demographics	●	●	●
	Globalization	●	●	–
	Economy/GDP	●	●	●
	Consumptive Behavior	●	●	●
	Technology	●	●	●
	Land use	●	●	●
	Biodiversity/conservation	●	●	●
	Equity	●	●	●
	MDGs	●	–	–
	Emissions	●	●	●
Actors	Public Institutions	●	●	●
	Private Institutions	●	●	●
	Civil Society	●	●	●
Sectors	Energy	●	●	●
	Water	●	●	●
	Agriculture & forestry	●	–	–
	Agriculture	–	●	●
	Forestry	–	●	–
	Transport	●	●	–
	Public Health	●	●	–
	Education	●	●	–
	Service	●	●	–
	Defense	●	●	–
	Telecommunications	●	●	–
	Entitlements	●	●	–
	Manufacturing	●	●	–
	Banking/Finance	●	●	–
	Natural Resource Extraction	●	●	–

Table 2. Information sources used in the development of storyline elements.

	Storyline Element	Global	National	Sub-national
Factors	Demographics	(O'Neill et al., 2014b; O’Neill et al., 2012)	(Bierwagen et al., 2010; Guarneri, 2009; IIASA, 2012a, b; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O’Neill et al., 2012; UNEP, 2007; USCB, 2012a, b)	(Bierwagen et al., 2010; IIASA, 2012a, b; Mackun, 2011)
	Globalization	(O'Neill et al., 2014b; O’Neill et al., 2012)	(Mintzer et al., 2003; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O’Neill et al., 2012; UNEP, 2007; WEF, 2010)	–
	Economy	(O'Neill et al., 2014b; O’Neill et al., 2012)	(CBO, 2014; IIASA, 2012a, b; Nakićenović and Swart, 2000; UNEP, 2007; USBEA, 2013; USBLS, 2012, 2013; WEF, 2010)	(Coakley et al., 2009; USBEA, 2013)
	Consumptive Behavior	(O'Neill et al., 2014b; O’Neill et al., 2012)	(Mintzer et al., 2003; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O’Neill et al., 2012; RF and GBN, 2010; UNEP, 2007)	(EIA, 2012a, b)
	Technology	(O'Neill et al., 2014b; O’Neill et al., 2012)	(EIA, 2012a; Mintzer et al., 2003; Nakićenović and Swart, 2000; RF and GBN, 2010; UNEP, 2007; WEF, 2010)	(IEA, 2012)
	Land use	(O'Neill et al., 2014b; O’Neill et al., 2012)	(Bierwagen et al., 2010; O'Neill et al., 2014b; O’Neill et al., 2012; UNEP, 2007)	(Bierwagen et al., 2010; MGCSCI, 2013)
	Biodiversity/conservation	(O'Neill et al., 2014b; O’Neill et al., 2012)	(Leadley et al., 2010; O'Neill et al., 2014b; O’Neill et al., 2012; UNEP, 2007; WEF, 2010)	(Keddy, 2009; NWF and SELC, 2013)
	Equity	(O'Neill et al., 2014b; O’Neill et al., 2012)	(IAF, 2008, 2011; Nakićenović and Swart, 2000; O'Neill et al., 2014b; O’Neill et al., 2012; UNEP, 2007)	(Oxfam, 2009)
	MDGs	(O'Neill et al., 2014b; O’Neill et al., 2012)	–	–
	Emissions	(O'Neill et al., 2014b; O’Neill et al., 2012)	(EIA, 2012a, b; Mintzer et al., 2003; Nakićenović and Swart, 2000; UNEP, 2007; USDOS, 2010)	(EIA, 2012a, b)
Actors	Public Institutions	–	(Mintzer et al., 2003; O'Neill, 2014; O’Neill et al., 2012; RF and GBN, 2010; UNEP, 2007)	(IEA, 2012; UNEP, 2007)
	Private Institutions	–	(Mintzer et al., 2003; RF and GBN, 2010; UNEP, 2007)	(Mintzer et al., 2003; RF and GBN, 2010; UNEP, 2007)

	Civil Society	–	(Mintzer et al., 2003; RF and GBN, 2010; UNEP, 2007)	(Mintzer et al., 2003; RF and GBN, 2010; UNEP, 2007)
Sectors	Energy	(O'Neill et al., 2014b; O’Neill et al., 2012)	(EIA, 2012a, b; Mintzer et al., 2003; USDOS, 2010)	(EIA, 2012a, b; IEA, 2012; Mintzer et al., 2003; NWF and SELC, 2013)
	Water	(O'Neill et al., 2014b; O’Neill et al., 2012)	(Li et al., 2011; Roy et al., 2005; Roy and Chen, 2011; Roy et al., 2012; Roy et al., 2010; UNEP, 2007)	(Li et al., 2011; Roy et al., 2005; Roy and Chen, 2011; Roy et al., 2012; Roy et al., 2010)
	Agriculture & forestry	(O'Neill et al., 2014b; O’Neill et al., 2012)	–	–
	Agriculture	–	(ERS, 2011; IFTF, 2011; UNEP, 2007)	(Malcolm et al., 2012)
	Forestry	–	(UN, 2012; UNEP, 2007)	–
	Transport	–	(EIA, 2012a, b)	–
	Public Health	(O'Neill et al., 2014b; O’Neill et al., 2012)	(IFTF, 2008; Makuc, 2008)	–
	Education	(O'Neill et al., 2014b; O’Neill et al., 2012)	(Anderson et al., 2012; Facer and Sandford, 2010; OECD, 2008, 2009)	–
	Service	(O'Neill et al., 2014b; O’Neill et al., 2012)	(CBO, 2014; USBLS, 2013)	–
	Defense	–	(NIC, 2012; USDOD, 2010, 2014)	–
	Telecommunications	–	(IGF, 2012; Lopez, 2012)	–
	Entitlements	–	(CBO, 2014; CMMS, 2012; IAF, 2011)	–
	Manufacturing	–	(MGI, 2011; PWC, 2012; UNEP, 2011)	–
	Banking/Finance	–	(WEF, 2010)	–
	Natural Resource Extraction	–	(UNEP, 2007; WEF, 2010)	–

Figure1 - SSPs Framework

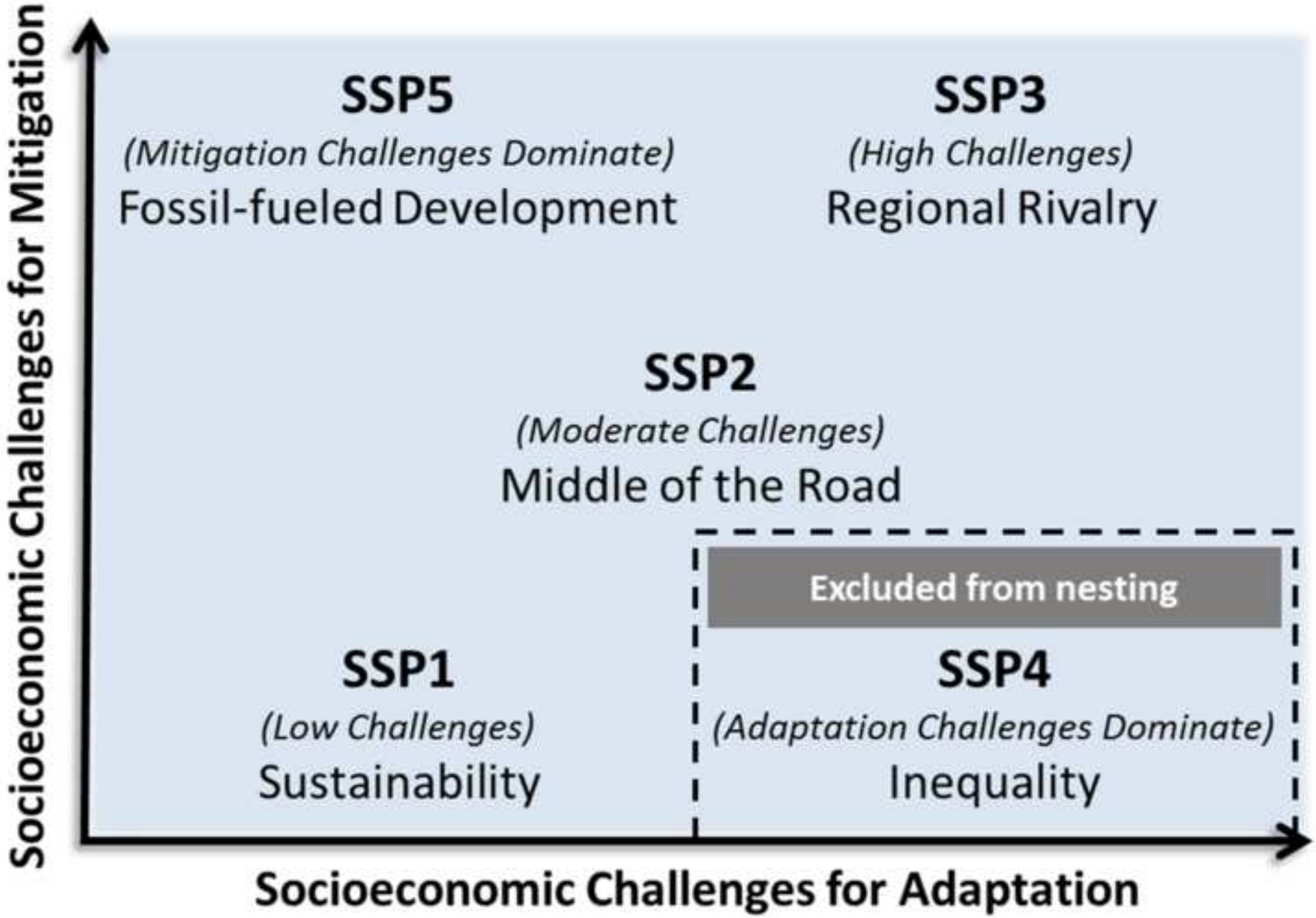

Figure2 - Coupling

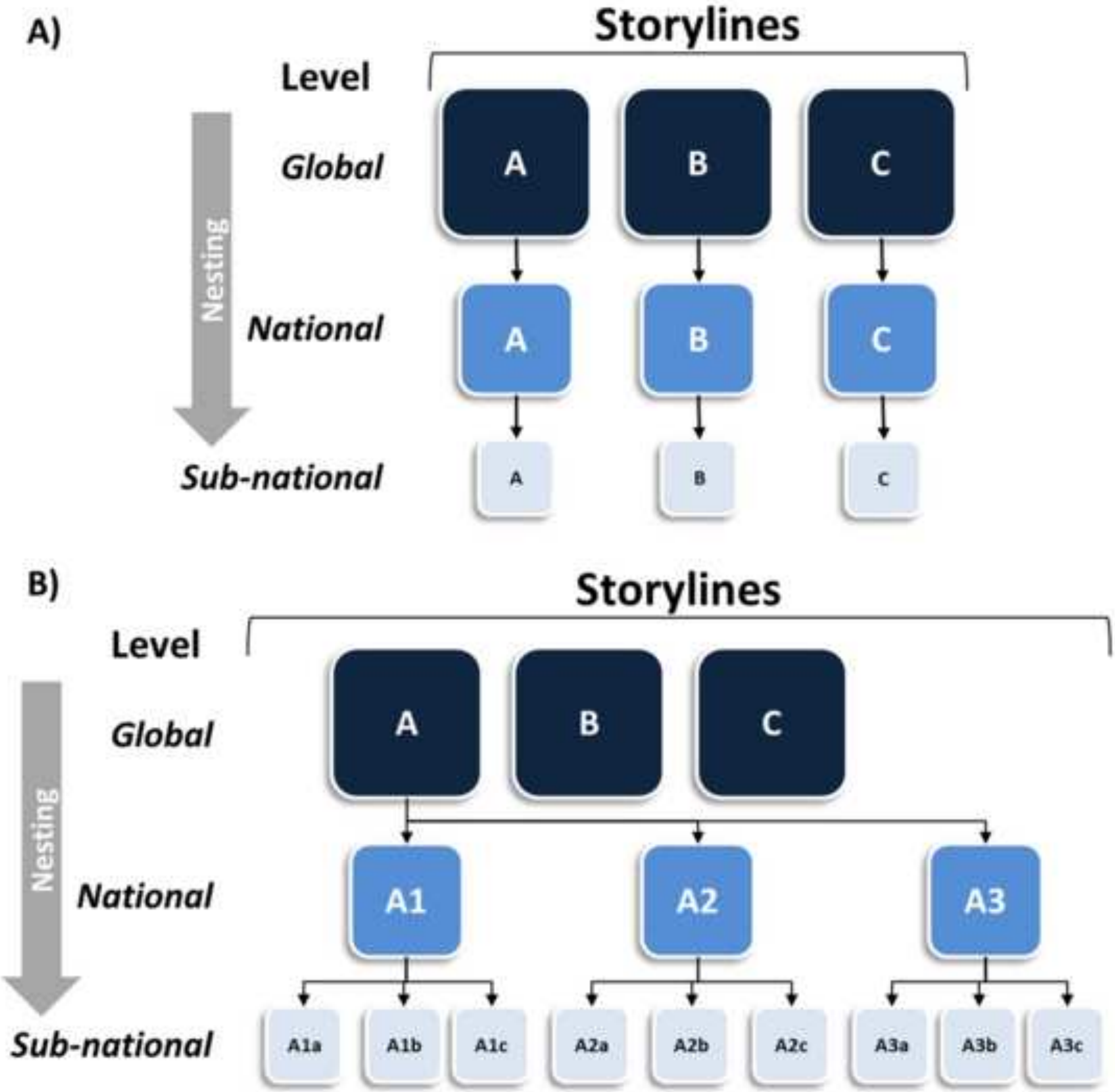

Figure3 - Nesting Framework

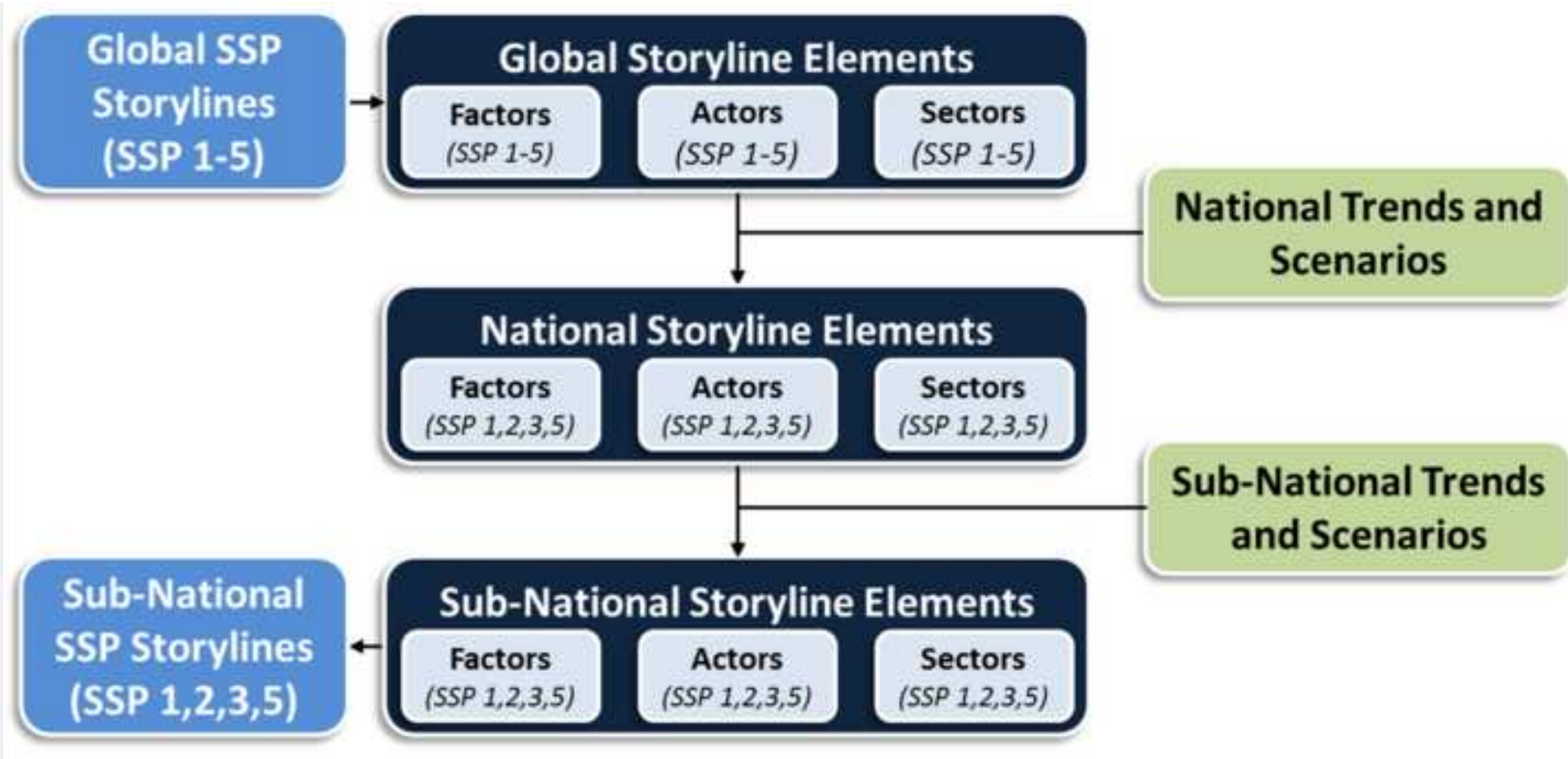

Figure4 - Population & GDP

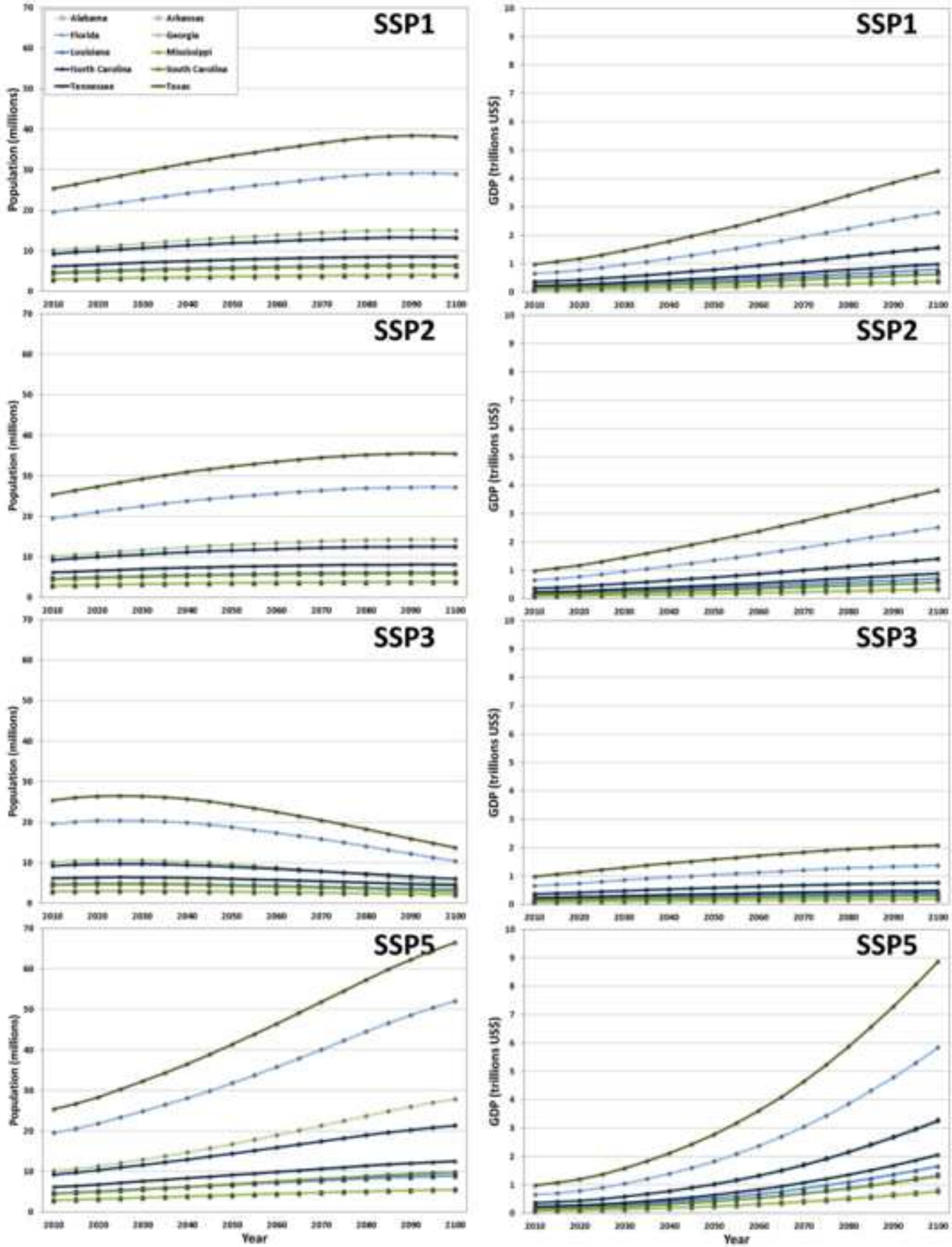

Figure5 - Water

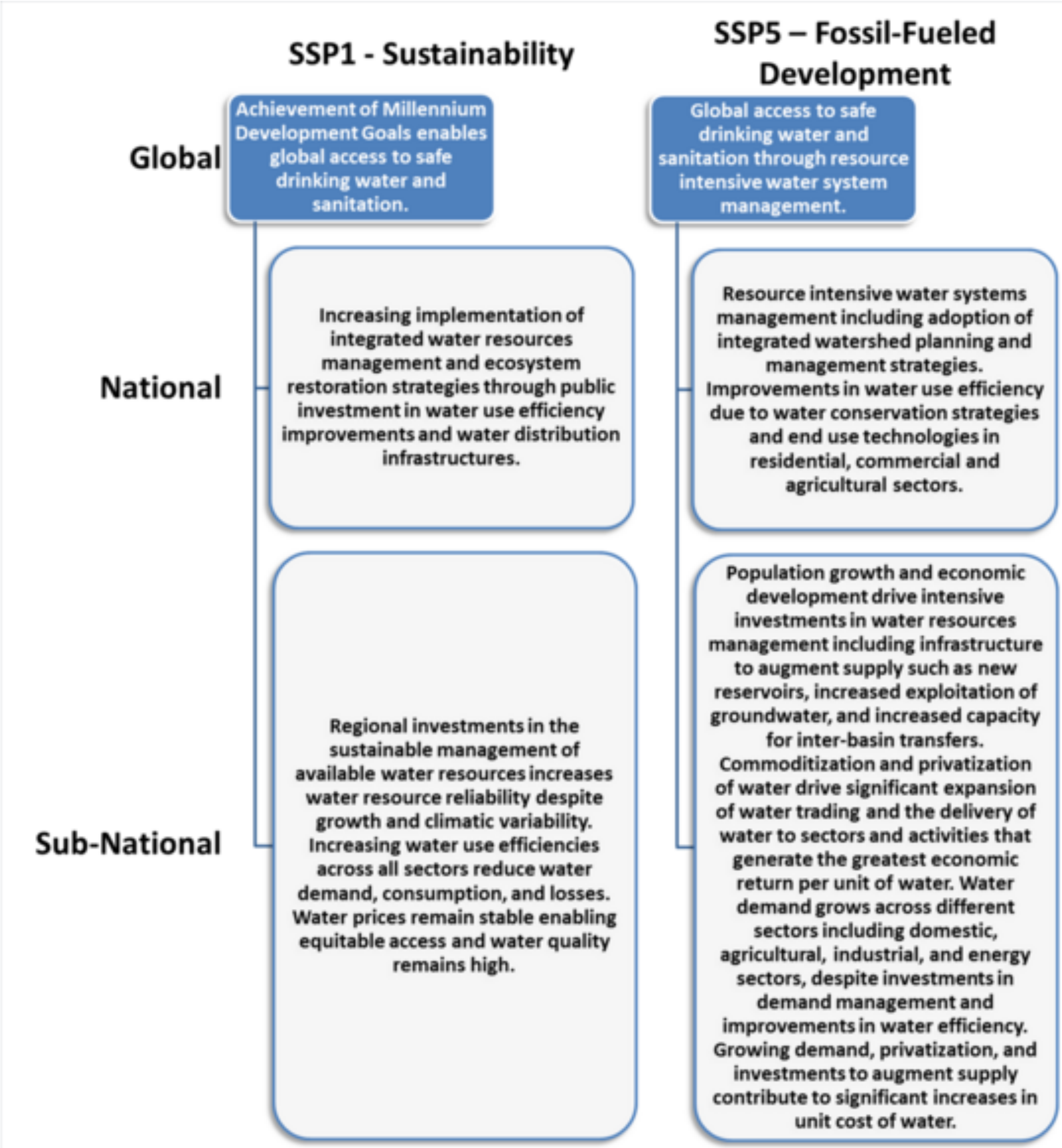

Figure6 - Synthesis