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A proposal for a new scenario framework to support research and assessment in different climate research communities

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ABSTRACT

In this paper, we propose a scenario framework that could provide a scenario "thread" through the different climate research communities (climate change – vulnerability, impact, and adaptation - and mitigation) in order to support assessment of mitigation and adaptation strategies and climate impacts. The scenario framework is organized around a matrix with two main axes: radiative forcing levels and socio-economic conditions. The radiative forcing levels (and the associated climate signal) are described by the new Representative Concentration Pathways. The second axis, socio-economic developments comprises elements that affect the capacity for mitigation and adaptation, as well as the exposure to climate impacts. The proposed scenarios derived from this framework are limited in number, allow for comparison across various mitigation and adaptation levels, address a range of vulnerability characteristics, provide information across climate forcing and vulnerability states and span a full century time scale. Assessments based on the proposed scenario framework would strengthen cooperation between integrated-assessment modelers, climate modelers and vulnerability, impact and adaptation researchers, and most importantly, facilitate the development of more consistent and comparable research within and across these research communities.

1. Introduction

Long-term global scenarios of the evolution of human and natural earth systems are an important tool for the assessment of climate change. The main rationale for using scenarios is that climate change is a slow process, where decisions today can have irreversible consequences for decades or even centuries. Large uncertainties play a role in exploring these consequences (e.g. for climate sensitivity, the carbon cycle, technology development and economic development). Scenario analysis has been developed as a tool to explore different futures under clearly defined assumptions. This simplification facilitates a focus on a finite number of potential future developments, particularly with regard to future states of socio-economic variables, e.g. energy, land use, land cover, emissions of greenhouse gases, aerosols and short lived species, and climate (Henrichs et al., 2010).

In climate research, scenarios are used by three broad sets of researchers: the climate modeling community, the integrated assessment modeling community, and the vulnerability, impacts, and adaptation community (corresponding also with the three working groups of IPCC) (Moss et al., 2010). Each group uses scenarios in different ways and for different purposes. The requirements for scenarios differ among these research communities, with different emphasis on scenario elements and different approaches. At the same time, the communities collaborate in their

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research and scientific assessment activities, for example, in the Intergovernmental Panel on Climate Change (IPCC), with IPCC's working groups corresponding to each of the three major research communities. While each community will inevitably use a set of very specific scenarios, it is also important to think about cases where information of all three research communities is used. Such studies would be able to illustrate the interactions among adaptation and mitigation responses, or deal more effectively with the challenge of understanding multiple stresses. There is a clear benefit from both a scientific and a policy perspective if some subset of scenarios provides a connecting and integrative thread that runs through the research assessed by all three communities. Currently, a set of new scenarios are being developed to support climate research in the next few years (Moss et al., 2008, 2010). More so than in earlier exercises, the new scenarios are intended to stimulate cooperation and coordination between the three research communities identified above.

The new scenario process began with the creation of Representative Concentration Pathways (RCPs); scenarios designed to help climate modelers explore the range of potential future greenhouse emissions and concentration pathways (Van Vuuren et al., 2011a). Following the development of the RCPs, Moss et al. (2010) calls for a "parallel phase" in which the climate modeling community uses the RCPs to develop ensembles of climate change scenarios while the integrated assessment modeling and 'vulnerability, impacts, and adaptation' communities jointly develop new scenarios. There are several key challenges involved in developing scenarios in this way. First of all, there are many factors that are relevant in the context of the research of three research communities. These factors somehow need to be grouped to form a limited, manageable and coherent set of common scenarios. A second challenge is that the relevant factors for mitigation and adaptation often act at different spatial and temporal scales. Scenarios therefore should be able to bridge these scales, by providing enough information on global trends and processes (e.g. international economic factors, international institutional factors and demographic trends) without over-determining local or sector scale processes or conditions that are best determined by local analysts in response to local user needs (Toth, 2003).

In this context, the purpose of this paper is to propose a scenario framework (including a definition of socio-economic scenarios) that could be used as the basis for new community scenarios that act as a thread for mitigation, adaptation and impact assessments and at the same time are consistent with the RCPs that define the climate dimension.

We divide this overarching question into several sub-questions in Section 2 – which are subsequently addressed in Sections 3, 4 and 5. For deriving these subquestions, we first describe the ongoing activities with respect to coordinated use of scenarios across the three research communities, focusing especially on the development and use of the RCPs (Section 2). In Section 3, we discuss the information needs of the integrated assessment and 'vulnerability, impacts, and adaptation' community. Next in Section 4, we discuss the information on some important socio-economic variables needed for integrated assessment and 'vulnerability, impacts, and adaptation community' work (as identified in Section 3) as included in the RCPs and in other scenario literature. Finally, in Section 5 we discuss a possible framework that may be used for future scenarios research. The same question is also looked at by Kriegler et al. (2010).

2. New scenarios and the role of the Representative Concentration Pathways

Over the last decade, the so-called SRES scenarios (Nakicenovic and Swart, 2000) have been extensively used in climate change research and assessments. The SRES scenarios (named after their publication, "Special Report on Emission Scenarios") provided six alternative descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about the key relationships and driving forces that could be used in combination with a set of climate model projections that employed the greenhouse gas emissions pathways of these scenarios. The SRES scenarios were based on narrative storylines that conveyed the overall logic underlying the related quantitative descriptions of future economic, demographic, technology, and emissions trends. These storylines highlighted two key uncertainties; the degree of international cooperation and the level of focus on sustainability issues. These narratives provided a framework that facilitated extrapolation of scenarios for other research. The data in the SRES scenarios were provided globally and for four broad regions.[1] This was adequate for their intended purposes of providing inputs to climate modeling and long-term global mitigation analysis, but additional efforts were needed to translate the scenarios to regional or national scales as needed for 'vulnerability, impacts, and adaptation' research purposes, in a meaningful way, e.g. by downscaling or developing additional "nested" scenarios (consistent with the global scenarios) (Van Vuuren et al., 2010).

According to Moss et al. (2010), there are three main reasons for developing a new set of scenarios. First of all, the SRES scenarios only considered developments in the absence of climate policy. Since then, a considerable amount of literature has emerged that looks into mitigation scenarios, responding to a shift in policy attention away from the need for climate policy to evaluate the costs and benefits of different types of climate policy (see Clarke et al., 2010; Edenhofer et al., 2010; Fisher et al., 2007; Van Vuuren et al., 2007). Second, new advances in climate models have led to a need for more detailed scenario information than was provided by SRES: aerosol emissions, geographically explicit descriptions of land use and emissions and detailed specification of emissions by source type. Third, there is a need for closer collaboration between the different disciplines involved in climate scenario formulation and use to allow for consistent usage of scenarios for the different objectives and methods of the modeling (as discussed in Section 1). This collaboration has been built into the design process for the new scenarios.

The process for developing the new scenarios is somewhat different than earlier exercises. It is intended to shorten scenario development time, while also promoting cooperation across the research communities. The development process consists of three phases: (1) the preparatory phase, (2) the parallel phase and (3) the integration phase. In the preparatory phase, four existing scenarios were selected from the published literature. The emission and concentration pathways associated with these four scenarios are referred to as Representative Concentration Pathways (RCPs). In the subsequent, parallel phase of the process, climate model runs are performed using the RCPs, while at the same time the integrated assessment and 'vulnerability, impacts, and adaptation' research communities develop appropriate storylines and new socio-economic scenarios (consistent with the RCPs) to inform research on both mitigation and adaptation. In the final integration phase, the results from the climate modeling and socio-economic narrative and quantitative scenario development activities will be brought together to form the final set of integrated scenarios.

The RCPs are intended to form a key element of the new process. They were selected to span a wide range for those factors that determine future climate change (radiative forcing of greenhouse gases and land use change). Each RCP was reviewed for internal consistency of the whole scenario, but only the information on emissions, concentrations and land use are released as the RCPs

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[1] OECD90, REF (primarily Eastern and Central European countries and newly independent states of the former Soviet Union undergoing economic reform), Asia (including centrally-planned Asia and China as well as other Pacific Asian countries), and Africa and Latin America.

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(Van Vuuren et al., 2011a). In a subsequent step, the integrated assessment and 'vulnerability, impacts, and adaptation' communities would work together on the desired characteristics for the socio-economic scenarios.

The RCPs have been selecting from existing literature to span the full range of possible trajectories for future greenhouse concentration through 2100. In total 4 scenarios were selected from 4 different modeling groups: a very high emission scenario leading to 8.5 W/m^2 (Riahi et al., 2007, 2011), a high stabilization scenario leading to 6 W/m^2 (Masui et al., 2011), an intermediate stabilization scenario leading to 4.5 W/m^2 (Clarke et al., 2007; Thomson et al., 2011) and a low mitigation scenario (2.6 W/m^2) (Van Vuuren et al., 2007, 2011b). The original scenarios were further processed to harmonize base year emissions and land use.

The new scenarios are thus intended to connect work on climate change, impacts and adaptation and mitigation. In this paper, we concentrate on the role of scenarios as an input for analysis of potential climate change impacts and the role of adaptation in ameliorating them, while at the same time considering the interplay between mitigation and adaptation. We discuss a parallel phase approach for the integrated assessment and 'vulnerability, impacts, and adaptation' communities to collaborate in the development of socio-economic narratives and scenarios that can supplement the RCPs and facilitate research coordination across 'vulnerability, impacts, and adaptation' and mitigation studies.

In Section 2, we indicated that the main focus of this paper is the question: to propose a scenario framework (including a definition of socio-economic scenarios) that could be used as the basis for new community scenarios that act as a thread for mitigation, adaptation and impact assessments while also being consistent with the RCPs that define the climate dimension. Based on the discussion in this section, we can subdivide this into three subquestions:

(1) What are the main dimensions and characteristics of socio-economic scenarios that provide sufficient context for both 'vulnerability, impacts, and adaptation' and mitigation analysis and what are the required components for a common socioeconomic thread? (Section 3)?
(2) Can available socio-economic information underlying the RCPs and other scenario studies be easily used to support such a common scenario framework (Section 4)?
(3) Is it possible to develop a scenario framework for mitigation, adaptation, and impact assessment (Section 5)?

For question 1, we first discuss the information needs of 'vulnerability, impacts, and adaptation' and mitigation analysis (Section 3.1/Section 3.2) and next derive a set of criteria for scenarios that could act as a thread between these communities. We also indicate a set of crucial indicators (Section 3.3/Section 3.4).

For question 2, we first look into a set of key socio-economic variables for IAV and mitigation analysis (derived in Section 3) and discuss whether the information in the socio-economic scenarios underlying the RCPs and other scenario literature can be directly used to build up a common scenario framework, or, in case it cannot be used directly, what this information implies for such a framework. The same question is also addressed by looking into the type of scenarios available in the scenario literature in general. In Section 3.4, this information is used to derive a set of key conclusions for a future scenario framework.

Finally, in Section 5 we propose a framework that could form the basis of joint impact/mitigation analysis, on the basis of the information needs and criteria derived in Section 3, and the assessment of current scenario work in Section 4.

3. Main dimensions and characteristics of scenarios useful for joint impact/mitigation analysis

3.1. Vulnerability, impact, and adaptation analysis

The consequences of changes in climate for society depend not only on climate variables, but also on characteristics inherent to the exposed system (Parry et al., 2007). Drawing from a non-climate change example, the importance of different socio-economic contexts in determining "damages" from a natural disaster can be seen in the very different impacts that occurred in Chile and Haiti in response to earthquakes during 2009 and 2010. In Haiti, where the death toll was high and damage extensive, infrastructure was poorly maintained and designed, internal emergency response capacity was low, and local resources for long-term recovery were very limited. In Chile, on the other hand, better basic infrastructure and superior response capacity was credited with limiting mortality and physical damage, while greater financial capacity, better education, better institutions and greater access to technical resources contributed to hastening recovery and rebuilding efforts.

In the climate change impacts literature, the extent to which the system is unable to cope with a hazard is often referred to as "vulnerability" (Füssell, 2007; Füssell and Klein, 2006; Klein et al., 2007; Moss and Malone, 2001; O'Brien et al., 2004; Parry et al., 2007), although this is described somewhat differently in different studies. In order to describe the future vulnerability, qualitative and quantitative information on societal developments (such as those captured in socio-economic scenarios) are used. In contrast to mitigation, societal development trends are more important for adaptation than specific climate policy. Thus, the assessment of vulnerability, impacts and adaptation requires not only a description of expected climate change, but also associated a description of socio-economic conditions. In brief, vulnerability to climate change is typically seen as a function of exposure (exp), sensitivity of the exposed system (sens) and adaptation capacity (AC), thus V = f (Exp, Sens, AC). "Impact" is usually interpreted as the combination of the first two factors.[2]

Future exposure to climate change is related to biophysical factors such as changes in average temperature, precipitation as well as extreme weather events, but also indirect changes like river flows. Projections of future exposure to climate variables are made by climate models or specific impact models. They are related to both natural climate variability and forcing factors (e.g. volcanic aerosols, variations in solar output) and to changes in climate that result from the anthropogenic forcing factors that define the RCPs (concentrations of greenhouse gases and air pollutants and land use) – although clearly uncertainty exists in the response of the climate system to forcing. As impacts occur in particular places at local to regional scale, downscaling methods are sometimes used to translate the coarse information of climate models to the relevant geographic scale. Sensitivity is the extent of change in the structure or function of a system as a result of exposure to climate change. It is a function of the assets exposed to change, which is dependent on a range of socio-economic conditions, including population change, economic development, and technological change.

Future vulnerability is more complex. This is partly because there are a very large number of factors that determine future vulnerability which are highly dependent on context and scale of analysis. It is influenced by the magnitude of the exposed system (e.g. number of people at risk), the sensitivity of the exposed system (e.g. the potential impacts on the affected system per unit

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[2] Note that "Vulnerability" is sometimes used to refer specifically to the last two factors.

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of climate change), and the adaptive capacity. The literature indicates that adaptive capacity is influenced by factors that are difficult to quantify, such social capital (Adger, 2003), institutions and governance, technological capabilities and level of economic development (Brooks et al., 2005), and scenarios for these influences are easiest to define in narrative terms. Climate vulnerability is therefore a function of an interaction between social and biophysical vulnerabilities, interpreted in quantitative and qualitative ways. Proximal vulnerabilities commonly mentioned in the literature include sensitivity, coping and adaptive capacities, hazard, and exposure, all of which processes occur at multiple scales with cross-scale interactions (Preston and Stafford-Smith, 2009). Adding likelihoods to the components of vulnerability leads to an expression of risk. Risk is a useful notion for policy-relevant impact assessments, but it remains controversial to make operational due to the fundamental uncertainties and subjectivities of assigning likelihoods. Attempts have been made usually on the basis of expert elicitation, such as by Morgan et al. (2006) and Zickfeld et al. (2007, 2010).

In current impact studies, the future impacts are assessed in a variety of ways. In part of the studies, socio-economic conditions are not treated explicitly or are unrealistically held constant (Berkhout and Hertin, 2000). Sometimes, relevant socio-economic conditions can be derived by "downscaling" the information on the socio-economic drivers of scenario studies such as population and economic development (Van Vuuren et al., 2010). But at the same more specific information on local and short-term factors (including policy) can be accounted for. Each of these methods has strengths and weaknesses associated with it, and should properly be used only for those analyses for which they are appropriate. There are several examples of studies that used SRES socio-economic development pathways (population, GDP, employment, etc.) downscaled to the local level (Carter et al., 2004; Martens et al., 2006; Rounsevell et al., 2008). For many other 'vulnerability, impacts, and adaptation' studies, which seek to embed analysis of the potential robustness or performance of different locally- (or sectorally-) relevant adaptation strategies within the broader context of uncertain socio-economic or climate futures, it is better to use locally-derived scenarios reflecting development choices that can be embedded in broader "bounding scenarios" of future global development and climate trends. Berkhout et al. (2002) and Zurek and Henrichs (2007) describe a potential application of this approach. A key area of cooperation between the integrated assessment and 'vulnerability, impacts, and adaptation' research communities is developing narrative storylines and socio-economic scenarios of development pathways that focus on trends at the scale of the international system and large regions. For reasons stated earlier, it is desirable that for some of these scenarios, an analytic relationship between the socio-economic conditions and RCPs be maintained, so that internally-consistent scenarios of climate change and socio-economic futures can be applied. Identifying the content of these scenarios requires cooperation between 'vulnerability, impacts, and adaptation' and integrated assessment researchers, so that the focus is properly on global forces that shape local conditions, rather than on trying to derive local conditions from global processes, conditions, or models that are not appropriate for this purpose and that do not reflect the interest of the local decision-makers for the specific topic at hand. Proper reflection of these cross-scale dependencies will require a system in which scenarios can be nested at different geographic levels.

3.2. Mitigation analysis

A key part of the mitigation literature concentrates on the feasibility of different climate targets, often defined by concentration or radiative forcing levels, and the associated costs (Clarke et al., 2010; Edenhofer et al., 2010; Fisher et al., 2007; Weyant et al., 2006). Research and assessment have identified critical factors in mitigation scenarios (Fisher et al., 2007):

(1) Factors that are part of the socio-economic assumptions underlying the scenarios, such as population growth, economic growth, technology development and societal preferences with respect to fuel choice;
(2) The assumed form of international climate policy (the level of participation of different countries and sectors; the coverage of various gases);
(3) The assumed instrumentation of climate policy (carbon tax; cap-and-trade; regulation etc.);
(4) The assumed availability and improvement of different technologies;
(5) The ambition of the climate policy.

So-far, a large part of the literature has concentrated on so-called 'first-best' worlds, that assume an optimal situation for international policy (full participation; i.e. factor b), instrumentation (international tax or cap-and-trade; factor c), and technology (no deliberate exclusions; factor d). The IPCC report also concluded that there was a clear correlation of mitigation costs with the underlying socio-economic assumptions (Fisher et al., 2007; Morita and Robinson, 2001).

Since AR4, several studies have focused on estimating the influence of non-optimal situations for factors b–d, generally referred to as 'second-best' worlds (examples include Clarke et al., 2010; Edenhofer et al., 2010; Rao et al., 2008; Tavoni and Tol, 2010). Not only do these scenarios result in higher mitigation costs, in some cases, ambitious mitigation targets are found to be unachievable. In the coming years, several integrated assessment model comparison projects will focus on this line of research. Planned research projects include identifying the costs of various climate targets as function of technology and climate policy assumptions (EMF-24) and the reproduction of the RCPs using additional integrated assessment models. Identification of costs as a function of various assumptions about future climate policy is identified as a key priority.

It should be noted that most global scenario exercises to date, including SRES, have generally taken a relatively positive approach by assuming continued economic growth, an often decreasing (relative) income gap between developing and industrialized countries, and sustained technological advances. Extreme scenarios which make very different assumptions or deal with abrupt social and economic changes are generally not considered. Also, the potentially negative feedback of possible large climate change impacts on general development patterns are generally ignored.

3.3. Integration of impact and mitigation analysis: potential role of RCPs and scenario literature

3.3.1. Key factors for relevant scenarios

For Sections 3.1 and 3.2 several key factors can be identified that would determine the relevance of socio-economic scenarios for future assessment of vulnerability and impacts in combination with mitigation.

(1) **Limited number**. The set of scenarios should be as small as possible, consistent with other scenario design criteria. One of the central roles of scenarios is to provide focus. A small number of scenarios can perform the role of tying together information from all climate research communities and could therefore be the foundation for a synthesis for policy makers.

Scenario usefulness in that regard degrades as the number of scenarios becomes large.

(2) **Comprehensive**. The framework needs to cover sufficiently different future development to represent a plausible range of assumptions and thus represent relevant uncertainties. Within this framework, RCPs can provide this range for climate outcomes. These need to be combined with ranges of socio-economic pathways and qualitative information (or storylines), addressing the interplay between mitigation, adaptation as well as resulting impacts that future societies might have to cope with.

(3) **Comparability**. The scenario set should make it possible for at least some research knowledge generated in one community to be compared with information generated n another community. For example, the cost estimates generated by a mitigation scenario should be predicated on similar key assumptions as the information generated with regard to impacts and adaptation. For example, if the mitigating world has low income and poor social organization skills, then it would be extremely useful to have information about climate change, climate impacts and climate adaptation predicated on those same income and societal characteristics.

(4) **Vulnerability and mitigative capacity**. Relevant dimensions include those that determine vulnerability (adaptive capacity and sensitivity) and mitigative capacity (baseline assumptions and the level of participation in international climate policy). The IPCC Third Assessment Report concluded that ‘‘both mitigation costs and net damages, in turn, depend on some crucial baseline assumptions: economic development and baseline emissions largely determine emissions reduction costs, while development and institutions influence vulnerability and adaptive capacity’’ suggesting that it might be possible to define relevant axes for both research areas (IPCC, 2001). The scenario set should provide a mechanism for understanding the range of differences between potential socio-economic circumstances for mitigation, impacts and adaptation.

(5) **Information across climate outcomes**. The set of scenarios should provide a means of tying information from all three climate research communities together in a way that highlights the differences between alternative potential climate futures. For example, it would be extremely useful to document the differences between a world that limits radiative forcing to 2.6 Wm^{-2} in 2100 and one which limits radiate forcing to 4.5 Wm^{-2}. Whereas previous assessments concentrated on illustrating the outcomes of scenarios that did not include climate policy, AR5 could begin to generate information that would inform more precise decision making by articulating implications for mitigation, climate change, impacts and adaptation decisions given different assumptions about climate forcings. Similarly, the scenarios should provide information about how mitigation, impacts and adaptation differs against alternative socio-economic backgrounds.

(6) **Multiscale**. The storylines need provide enough explicit information on the aggregated scale to be clearly distinguishable. This is an additional reason for a small number of scenarios. At the same time, they need to provide enough flexibility for interpretation at more detailed scales or consistent incorporation of scenarios developed for lower levels of scale (regions or sectors).

(7) **Time scales**. The scenario set should enable information about mitigation, impacts and adaptation at short, mid and long time scales. That is, for time frames ranging from the present to 2100 with some time intervals.

(8) **Structured but flexible**. The scenario set should provide enough structure to facilitate consistency and offer context and calibration points for the various ‘vulnerability, impacts, and adaptation’ and mitigation analyses. However, the set should not be too prescriptive, but instead offer flexibility for defining relevant details, as well as opportunities for exploring uncertainties.

Finally, we recognize that many impact and mitigation analyses are still based on SRES. It would be useful if the framework could provide a broad enough taxonomy to retain comparability to these ongoing assessments. It is worth noting that the scenario framework we propose would be a thread through integrative climate research (and AR5 in particular). The framework, however, is not intended to be comprehensive. It is not intended to span all possible dimensions in any realm. For example, the particular set of climate forcings leaves potentially interesting cases, such as for example stabilization at 3.7 $\mathrm{W/m}^2$, unexplored. Similarly, a small set of scenarios would be unable to explore all of the dimensions vulnerability. Many scenarios developed for specific question within each research community will be developed outside the framework. For example, integrated assessment researchers are already exploring the roles of key characteristics such as technology and policy architecture (Clarke et al., 2010; Edenhofer et al., 2010). As long as these are formulated as typical mitigation questions they would be unexplored within the context of the ‘‘thread’’ scenarios.

3.4. Components for a common socioeconomic thread

Based on earlier scenario exercises and the criteria formulated in the previous section, a common socioeconomic thread could consist of three components that can be adopted by the vast assortment of climate researchers: (1) a common conceptual framework; (2) simple socio-economic narratives and (3) a lean set of quantified variables.

The components need only provide a common structure and external context that will offer consistency and calibration points. They should not be overly prescriptive and instead offer researchers plenty of flexibility for specifying details and exploring sensitivities. In a subsequent section we propose a broad conceptual framework for framing options and issues to consider in developing a scenarios design. To characterize the state of the literature and reflect upon scenario needs, we first consider current socioeconomic scenarios relative to the RCPs. Narratives are a valuable means for providing qualitative context and guidance for the development of detailed supplemental information to accompany the variables provided with the thread. As for quantification, a limited number of variables are prudent to provide a skeleton of consistent information on which researchers can hang details relevant to their research and off of which they can explore uncertainties—sectorally, temporally, and spatially. Table 1 provides a list of candidate variables and resolution for supporting impact and mitigation research at many scales (but other variables may be added). Fine resolution socioeconomic results are certainly possible given downscaling techniques. However, they are more

Table 1
Examples of potential socioeconomic variables.

Variable (regional)	Resolution
Population	Region
Economic output (GDP)	Region & sector
Economic consumption	Region
Primary energy	Region & fuel
Final energy	Region, sector, & fuel
Land-use	Region, activity type, & grid
Agricultural production	Region & broad category
Net trade	Region & sector

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prescriptive and introduce another layer of uncertainty into the quantified information.

3.5. Position of the RCPs

As indicated earlier, the RCPs are an appropriate starting point for any framework as they will already form an important connection between integrated assessment and climate modeling research and assessment. In that context, the scenarios underlying each individual RCP provide an internally consistent description of population, income, energy, land use, other relevant driving forces and emissions. However, this is not the case for the set of RCPs. Each RCP and scenario originates from a different modeling team and comes from a specific study, with its own research questions and assumptions on future developments. There is therefore no *a priori* reason why the set as a whole would necessarily be representative of the literature for parameters other than radiative forcing (and directly related variables). Neither does the set *a priori* have an internal logic other than the radiative forcing characteristics on which it is based. It would, however, still be possible that other scenario characteristics would show clear correlation with radiative forcing. Very different modeling and socioeconomic scenarios generated by integrated assessment models can yield essentially indistinguishable concentration pathways, depending on many factors, among them the particular policy instruments chosen for implementation (Clarke et al., 2010).

In order to analyze the consistency of variables between scenarios, we have undertaken a literature review of the socio-economic ranges in the scenario literature, including the RCPs, in relation to radiative forcing level (Section 4). The analysis is based on three main sources. The first two are (1) the scenario literature as included in the scenario database compiled for IPCC AR4 (Fisher et al., 2007; Nakicenovic et al., 2006) and (2) the results of the recent model comparison project EMF-22 (Clarke et al., 2010). We have analyzed these sets to determine the relevant literature ranges and to look for evidence of correlation between socio-economic parameters and radiative forcing levels. In addition, we have used the socio-economic scenarios underlying the RCPs and RCP replications by other models within the RCP development process.

In this overview, we focus on the individual parameters (e.g. population, income, energy use) that are of critical importance for mitigation and 'vulnerability, impacts, and adaptation' issues. A crucial question for scenario development, therefore, is whether there are certain theoretically or historically derived relationships between the parameter values that make some combinations likely or unlikely. For instance, is there a reason to assume that the combination of low radiative forcing (i.e. RCP2.6) and high economic growth (or high population growth) is unlikely. The questions are complicated – as they relate to future trends (and historical evidence can therefore only be used with care). Therefore, instead we focus on the outcomes of models and have to assume that together these models provide a set of meaningful information.

It should also be noted that in our analysis we focus solely on results at the global level, (consistent with the questions raised in Sections 1 and 2 of this paper). The literature assessed for this paper mostly assumes full participation in climate policy (but not all). Finally, We refer to the scenarios underlying the RCPs as IM-2.6, GCAM4.5, AIM6.0 and MES8.5, in order to emphasize that the RCPs themselves only include the emission, land use and concentrations information. Together this set is referred to as the original RCP scenarios.

4. Socio-economic driving forces: comparison of the RCPs with available literature

4.1. Quantitative evaluation of the RCPs with respect to socio-economic driving forces

In our quantitative evaluation of the RCPs, we focus on 4 major parameters: population, income, primary energy use and CO_2 emissions. Note that while all four are of fundamental importance for mitigation research, only the first two are generally of relevance for 'vulnerability, impacts, and adaptation' research.

4.1.1. Population

Three of the four underlying scenarios for the RCPs are based on a global population scenario reaching 8.5–9.5 billion people in 2100. MES-8.5 forms an exception as it deliberately assumes a higher global population. The IM-2.6, GCAM4.5 and AIM6 scenarios all deliberately aim to follow an intermediate population pathway consistent with the medium UN projections published over the last few years and most of the population projections currently used in integrated assessment models (EMF-22) (Fig. 1).

In the EMF-22 set, no relation is observed between radiative forcing levels and population level (see Fig. 1). This is confirmed by plotting the population data in the EMF-22 data against the cumulative CO_2 emissions (correlating well with radiative forcing) in Fig. 2. It should be noted that population is exogenous to nearly

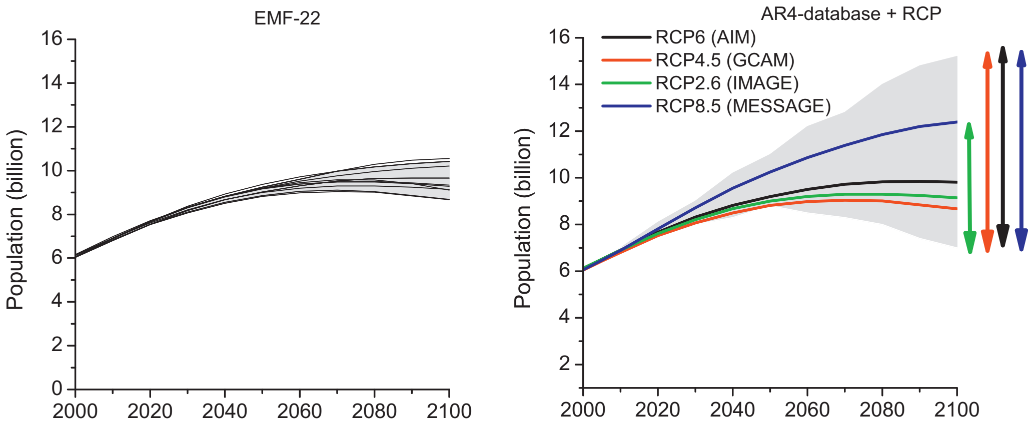

Fig. 1. Overview of population scenarios in the literature in relation to the RCP radiative forcing levels (scenarios from EMF22 (Clarke et al., 2010), the four RCPs (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; Van Vuuren et al., 2011b)), the scenario database used for AR4 (Nakicenovic et al., 2006). The arrows on the right depict the range of scenarios consistent forcing levels comparable to each RCP (colour codes). The grey area indicates the full uncertainty range in the literature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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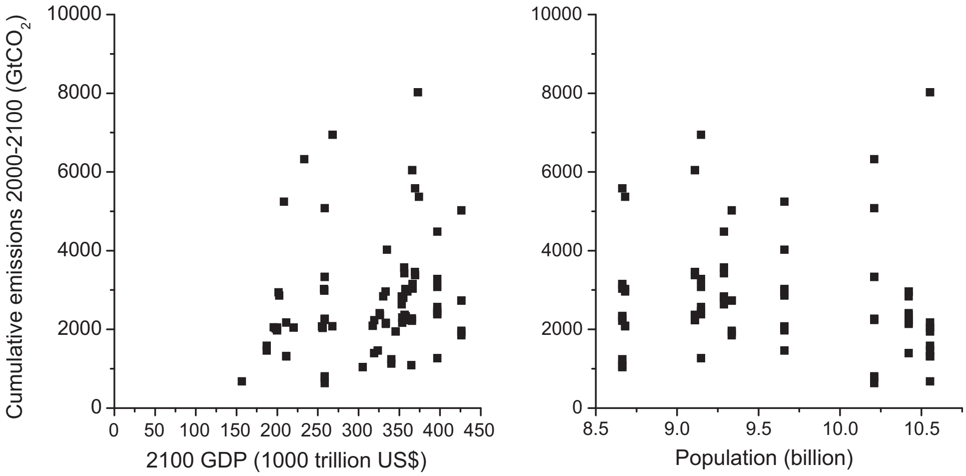

Fig. 2. 2100 income and population level in the EMF22 scenarios (Clarke et al., 2010) versus the cumulative CO_2 emissions from energy/industry sources. Cumultive CO_2 emissions correlate closely with the radiative forcing levels.

all models; thus, population for use in scenarios is typically derived from projections made independently of integrated assessment models. The range of population projections included in the AR4 database is much wider than the range drawn upon in for the scenarios underlying the RCPs. Many of the scenarios in the AR4 dataset deliberately explored the impacts of different storylines and their implications for demographic developments. Moreover, the database includes some relatively old scenarios (e.g. from 2000) that used higher population projections. Within this database, it can be shown that the range of population projections in the literature for the scenarios underlying the three highest RCPs (in terms of radiative forcing) is equal to the full literature range (excluding the extreme tails of the distribution). Interestingly, for the scenarios leading to radiative forcing levels consistent with the RCP2.6 a somewhat reduced population range is found, but even here the range still covers the highest of the original scenarios of the RCPs. In other words, a lower radiative forcing levels seems not to coincide easily with population levels above 12 billion. This is consistent with some earlier studies that reported that very low radiative forcing levels cannot be achieved from very high population levels.

4.1.2. Income

The total set of scenarios (IM2.6, GCAM4.5, AIM6 and MES8.5) behind the RCPs projects a GDP level ranging from 200 to 300 trillion US$ in 2100. These GDP levels are consistent with those reported in the recent scenario literature as part of the EMF-22 project. Within the set, AIM6 and MES8.5 show relatively low values and IM2.6 and GCAM4.5 relatively high values. One could formulate different hypothesis about expected relationships between income and radiative forcing levels. First, most models assume that (more) stringent climate policy will lead to costs and thus to (somewhat) lower GDP (everything else being equal). Second, lower levels of economic activity will make it easier to reduce emissions to very low levels. Third, a very slow development of GDP is likely to coincide with relatively slow technology development or ability to finance more costly technologies and implying higher emissions - the opposite relationship compared to that predicted by the first 2 hypotheses.

The EMF22 study provides some insight into these hypotheses on the relationship between climate target and GDP level. The data shows for most individual models there is a relationship of lower GDP levels with more stringent targets as a result of mitigation costs, leading to a loss of per cent GDP. The differences across the scenarios of different models are in fact much larger. Apparently, other factors (often exogenous assumptions to the models and the causal relationships in the models) are much more dominant for economic growth than climate policy (see Figs. 2 and 3). This result is also seen for some of the RCP models when simulating other radiative forcing levels: while for the individual models more stringent climate policy leads to lower GDP the differences across the models are much larger. In the context of these finding one must conclude that the inverse order for the scenarios underlying the RCPs in terms of income is “coincidental”, i.e. based on independent model assumptions.

4.1.3. Primary energy consumption

The scenarios behind the 4 RCPs show a wide range of outcomes for future energy systems, both in terms of absolute consumption levels and the type of energy used. For simplicity, we focus only on the former here (Fig. 4). The lowest 3 RCPs result in a relatively narrow range of 2100 primary energy consumption levels of between 800 and 1100 EJ/year; in contrast the highest RCP leads to primary energy consumption of 1750 EJ/year. These numbers are consistent with those of the EMF22 model comparison. Also here, the reference scenario range is significantly higher than the range for mitigation scenrios (around 700 EJ/year). The reason is that mitigation cases rely on vigorous efficiency improvements. Interestingly, it seems that the difference between 4.5 and 2.6 W/m^2 scenarios is relatively small. This finding is somewhat consistent with a conclusion reached by individual model studies that for more stringent scenarios an increasing share of emission reduction comes from changes in energy supply.

The same story can be seen for the alternative projections of the RCP models: model specific assumptions are the dominant determinant of future energy consumption, but for each model more stringent targets lead to lower energy consumption. Finally, in the AR4 database, it can be observed that the lowest mitigation scenarios have a more confined range for future primary energy consumption – but no distinction can be made for the other radiative forcing levels.

4.1.4. Emissions (CO_2 emissions from energy/industrial sources)

For emissions from energy and industrial sources, as expected, a strong correlation between the emissions and radiative forcing level is observed in all studies (Fig. 5). The results across the various studies (RCPs, AR4, EMF-22) are consistent, showing low greenhouse gas emissions are needed for low radiative forcing targets and very similar trajectories.

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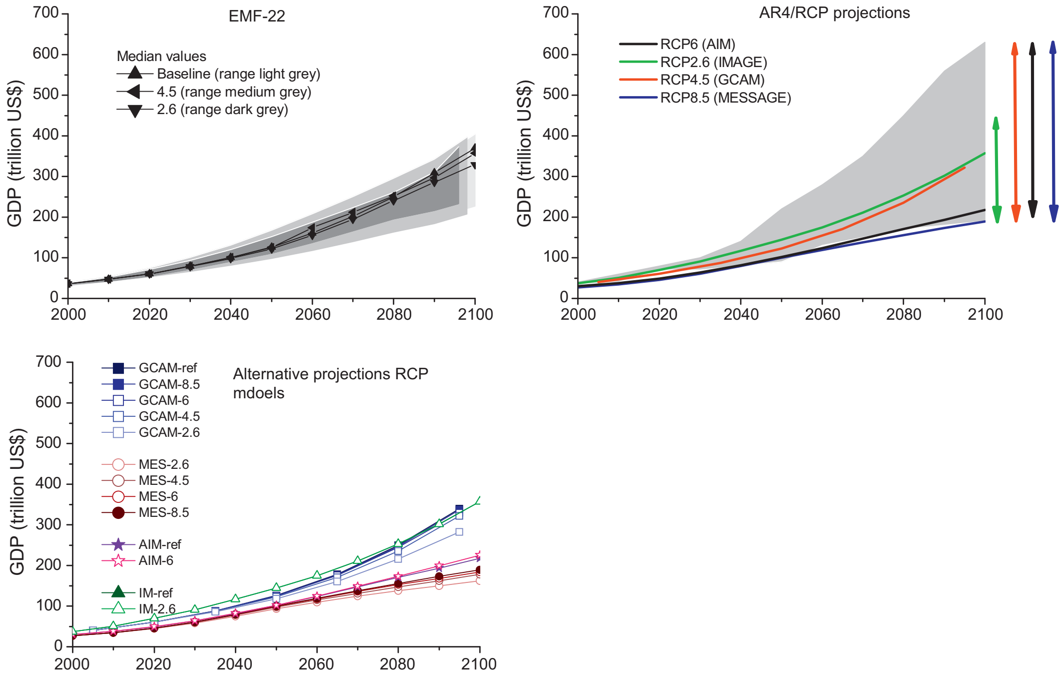

Fig. 3. Overview of GDP scenarios in the literature in relation to the RCP radiative forcing levels (scenarios from EMF22 (Clarke et al., 2010), the four RCPs (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; Van Vuuren et al., 2011b)), the scenario database used for AR4 (Nakicenovic et al., 2006). The arrows on the right uper graph depict the range of scenarios consistent forcing levels comparable to each RCP (colour codes). The grey area indicates the full uncertainty range in the literature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

4.2. *Evaluation of other storyline elements in the literature*

In addition to the four elements focused at Section 4.1, there are some other elements that are emphasized in the scenarios underlying the RCPs – most of these elements are of greatest relevance to mitigation, because the scenarios were developed primarily to explore GHG emissions - that can be directly used in our evaluation.

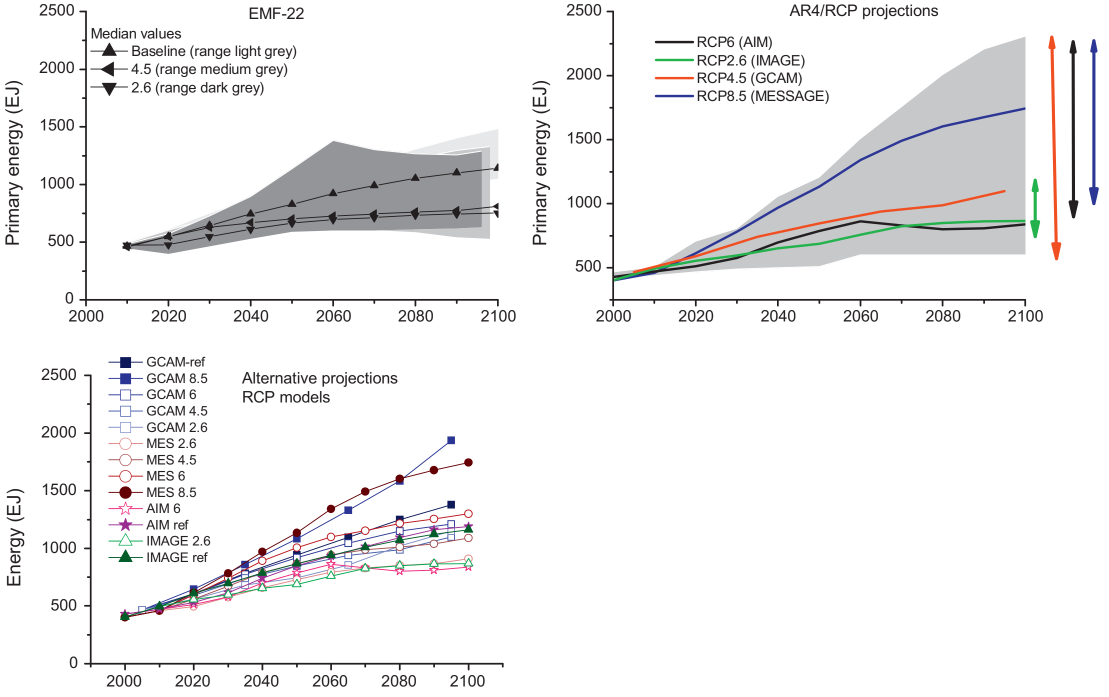

Fig. 4. Overview of primary energy consumption in the scenarios in the literature in relation to the RCP radiative forcing levels (scenarios from EMF22 (Clarke et al., 2010), the four RCPs (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; Van Vuuren et al., 2011b)), the scenario database used for AR4 (Nakicenovic et al., 2006). The arrows on the right uper graph depict the range of scenarios consistent forcing levels comparable to each RCP (colour codes). The grey area indicates the full uncertainty range in the literature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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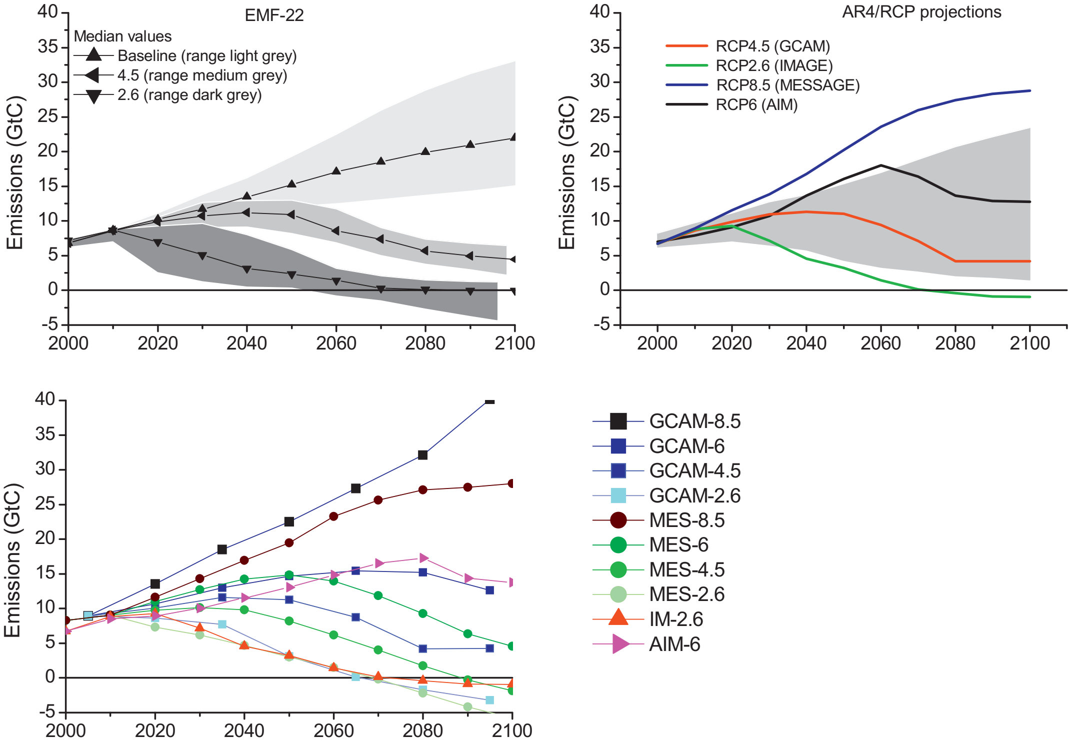

Fig. 5. Overview of CO_2 emission from energy/industry in the scenarios in the literature in relation to the RCP radiative forcing levels (scenarios from EMF22 (Clarke et al., 2010), the four RCPs (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; Van Vuuren et al., 2011b)), the scenario database used for AR4 (Nakicenovic et al., 2006). The grey area indicates the full uncertainty range in the literature).

(a) The MES8.5 scenario follows an explicit storyline. This scenario assumes little international cooperation and consequently little technology development and a high reliance of large Asian economies on domestic coal resources (consistent with the SRES A2 scenario).

(b) The RCP2.6, in contrast, emphasizes that the stringent climate policies assumed are only possible in the case of strong international cooperation and considerable technology progress. These conditions would also increase adaptive capacity.

(c) For the RCP4.5 and RCP6 scenarios, international climate policy is also assumed (and thus international cooperation). Given the relatively higher flexibility with respect to emission reduction, these assumptions are less critical. The 4.5 stabilization case, while requiring international cooperation and mitigation policies, can be reached by a large number of models even assuming delayed participation by some regions (Clarke et al., 2010).

In the literature, different approaches can be seen with respect to the emphasis of the storylines behind scenarios. The use of explicit storylines to provide consistent scenario sets has, mostly in response to the SRES work, been regularly applied in international environmental assessments. In contrast, in more recent mitigation studies there has been less focus on explicit storylines. Such studies often use the more traditional approach whereby one reference scenario depicts developments in the absence of climate policy, and is compared to several alternative cases with climate policy. In this approach, the focus on too many alternative storylines for the baseline is assumed to make the analysis too cluttered. For those studies that use explicit storylines, however, several common elements can be recognized. In current assess-

Table 2
Characteristics of the storylines in the literature (archetypes versus important scenario characteristics) as identified by Van Vuuren et al. (2011c) based on the Millennium Ecosystem Assessment (Carpenter and Pingali, 2006), IPCC SRES (Nakicenovic and Swart, 2000), UNEP's Global Environmental Outlook (UNEP, 2002; UNEP, 2007) and the International Assessment of Agricultural Science and Technology Development (Watson, 2008).

	Economic optimism	Reformed markets	Global sustainable development	Regional sustainability	Regional competition	Business-as-usual
Economic development	Very rapid	Rapid	Ranging from slow to rapid	Medium	Slow	Medium
Population growth	Low	Low	Low	Medium	High	Medium
Technology development	Rapid	Rapid	Ranging from medium to rapid	Ranging from slow to rapid	Slow	Medium
Environmental technology development	Rapid	Rapid	Rapid	Medium to rapid	Slow	Medium
Main objectives	Economic growth	Various goals	Global sustainability	Local sustainability	Security	Not defined
Environmental protection	Reactive	Both reactive and proactive	Proactive	Proactive	Reactive	Both reactive and proactive
Trade	Globalization	Globalization	Globalization	Trade barriers	Trade barriers	Weak globalization
Policies and institutions	Policies create open markets	Policies targeted at market failures	Strong global governance	Local actors	Strong national governments	Mixed
Vulnerability	Medium-high	Low	Low	Possibly low	Mixed	Medium

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Table 3
Ranges for 2100 population, GDP and emission levels of scenarios in the literature consistent with the various RCP levels (scenarios from EMF22 (Clarke et al., 2010) and the scenario database used for AR4 (Nakicenovic et al., 2006) (average number in each category + 10–90th percentile interval). For RCP2.6, RCP4.5 and RCP6.0, all scenarios in the corresponding IPCC category were used (Fisher et al., 2007); for RCP8.5 scenarios were used in the category "no climate policy" with cumulative CO_2 emissions corresponding to 8.5 W/m^2.

	2100 Population (billion)	2100 GDP (2100–2000 ratio)	2100 CO_2 emissions (GtC/yr)
RCP2.6	9.3 (7.1–10.5)	9.4 (7.2–12.1)	−0.21 (−3.8 to 1.7)
RCP4.5	9.7 (7.1–14.8)	9.9 (6.1–15.7)	5.6 (3.1–8.4)
RCP6.0	10.4 (7.1–15.1)	12.5 (7.2–20.1)	12.7 (8.7–16.9)
RCP8.5	11.0 (7.1–15.1)	13.4 (7.5–20.5)	34.2 (27.9–39.7)

ment literature specific scenarios families can be recognized (Van Vuuren et al., 2011c). These common elements have been summarized in Table 2. As these storylines are defined by many different aspects they also partly define the vulnerability of society to climate change and therefore can provide a possible linkage to 'vulnerability, impacts, and adaptation' analysis. The table provides a possible suggestion of the vulnerability designation (column) of each storyline element (row).

4.3. Conclusions

We realize that there are limitations to the study presented in Section 4.1 (e.g. selection bias for low scenarios all assuming full participation; no statistical analysis and focus on the global level). Still, we believe that the analysis above lead to the following suggestions:

- There is a broad set of socioeconomic projections consistent with each of the different radiative forcing pathways. This is in fact confirmed by Table 3 where the same data is presented by indicating the scenario ranges for population, income and CO_2 emissions in 2100 for scenarios consistent with each of the RCP levels. For the first 2 parameters, the ranges for each RCP level strongly overlap (with a few noticeable exceptions mentioned in Section 4.1). For CO_2, there is no overlap given the strong correlation with the radiative forcing target.
- Scenarios are available that reach each radiative forcing level from a very wide range of sets of population, income, energy, and other assumptions. There is some weak evidence that very low emissions levels are not likely for very high income or population assumptions.
- For individual studies, there often is a relationship between income and radiative forcing level (for models that include a feedback of mitigation on economic growth) such that stricter targets lead to reductions in income growth. However, the variation seems very modest when compared to the spread of assumptions on income growth across the full set of models.
- As a set, the scenarios behind the RCPs do not explicitly provide a logical framework for combining radiative forcing, income and population projections; nor do they cover the full range of possible outcomes for socio-economic variables or explicitly include many indicators of direct relevance to 'vulnerability, impacts, and adaptation' research. However, each RCP scenario individually is based on a consistent combination of these variables.
- For primary energy consumption, there is some correlation with the RCP forcing levels due to the role of energy efficiency and reductions as a mitigation option. The correlation between RCP levels and emissions is, as expected, very strong.
- Especially for the low and high radiative forcing scenarios, the combination of elements in a storyline needs to be consistent with the forcing level. While apparently it is difficult to establish clear relationships with individual factors, In the end, a high forcing scenario does need either something like high population growth, low technology development, large significant reliance on coal use (or some combination of these) in order result in high emissions.

In fact, this formulation is very similar to the conclusion formulated in the SRES report: Similar future GHG emissions can result from very different socio-economic developments, and similar developments of driving forces can result in different future emissions (Nakicenovic and Swart, 2000). These conclusions imply that it is not advisable to directly use the original socio-economic pathways underlying the RCPs as a framework for impact analysis: they do not cover the literature ranges nor are they directly comparable to each other. Thus an alternative way to create useful storylines for impact and mitigation research in accordance with RCPs needs to be considered. Indeed, that was one of the motivations for the new "parallel process" of scenario development – to allow more time for development of socioeconomic storylines and scenarios that are constructed explicitly for exploration of 'vulnerability, impacts, and adaptation' research issues (Moss et al., 2010).

5. Proposed framework for analysis

5.1. An overarching scenario framework for combining RCPs with socio-economic pathways

In Section 3 we laid out a set of criteria for a scenario framework for comprehensive 'vulnerability, impacts, and adaptation' and mitigation analysis, based on the purposes of different scientific communities. As discussed above, the socio-economic information underpinning the RCPs provide only weak constraints for accompanying socioeconomic pathways for use in impact studies. This section thus presents a possible scenario framework that would combine new sets of socio-economic information (narratives and quantifications) with the RCPs.

Following our discussions in Section 3.1, future impacts will depend primarily on the exposure of the affected system (related in part to the strength of the climate change signal) as well as the system's sensitivity to and capacity to adapt to this signal.

The climate signal, which underlies exposure, is described by the climate model outcomes of the RCPs and is related to the extent of mitigation (in combination with baseline emissions) as well as expected climate-related exposure. In other words, the higher the climate signal, the greater the likely impacts and the more adaptation that is expected, while the lower the climate signal the more stringent mitigation efforts would need to be. The RCPs cover both actual climate change (in a certain year) as well the rate of change over time.

A second dimension of our framework describes the exposed system and the "capacity" of the system to mitigate or adapt. Clearly, this second dimension depends strongly on the extent, pace, and direction of future social, economic and political development. While there are many factors that can be used to characterize socio-economic development and the ability of societies and groups to deal with climate impacts and mitigation challenges, for simplicity we propose to translate this into one

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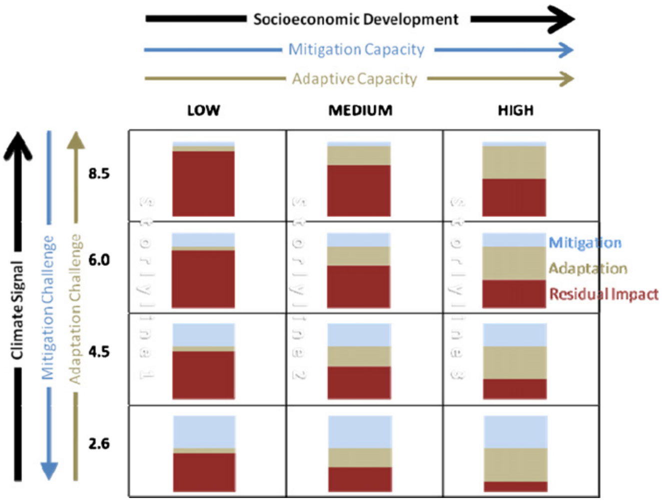

Fig. 6. Proposed framework for mitigation, adaptation and impact analysis on the basis of the RCPs (the vertical axis covers the climate signal based on the RCPs, including both current climate variables and the rate of change; the horizontal axis covers socio-economic storylines). Note that the bars just illustrate possible outcomes of analysis.

single "dimension". In general, effective governance, rapid technology development, high income growth, a high level of international cooperation and low population numbers are all conditions that coincide with a high capacity for both mitigation and adaptation. In contrast, the opposite conditions, in general terms, lead to low capacity for mitigation and adaptation. This leads to the hypothesis that the underlying socioeconomic conditions that favor high adaptive capacity also likely to favor high mitigation capacity. In AR4-WG2, similar reasoning was followed suggesting that adaptive capacity and sustainable development had the same underlying drivers (Klein et al., 2007). While clearly cases can be formulated where mitigative and adaptive capacity might not be coupled, we believe that the coupling of these factors to be justified for the purpose of formulating a simplified scenario framework. Alternatively, one may formulate different socio-economic scenarios along the second dimension that assume contrasting conditions for the capacity for adaptation and mitigation (Kriegler et al., 2010).

Putting these two dimensions on the horizontal and vertical axis of an impact matrix defines our scenario framework (Fig. 6). An important feature of the matrix is that its individual cells describe the interplay between adaptation and mitigation and the resulting residual impacts. Using the matrix as an organizing principle for research would allow researchers to explore a wide range of relevant combinations between contributing factors. For example, the combination of high climate signal with a low adaptive capacity in the upper left corner leads to a world with low adaptation, little mitigation and high impacts. In contrast, a world with a low climate signal, but favorable socio-economic conditions leads to a world with considerable mitigation action, some adaptation and relatively low impacts. The framework therefore allows exploration of the influence of different levels of the ambition of radiative forcing targets (as a function of baseline emissions and the target level; vertical axis), adaptive capacity and vulnerability (horizontal axis), or similar levels of impacts (diagonal axis) resulting from the combinations of mitigation and adaptation measures. One important aspect of the framework is that it includes a specific assessment of residual impact – that is, the climate change impacts that remain once adaptation has taken place. These impacts may be positive, but for the most part they will be experienced as irreducible damages.

An important step in making this scenario framework salient to the wider research community would be to define specific characteristics of the horizontal axis, i.e. correlating the columns of low, medium and high socio-economic development with the societies' capacity for mitigation and adaptation. The general storyline elements as listed in Table 2 form an important element, including in particular the role of institutions and their efficacy as well as governance structure, the extent of global cooperation, the rate of technology innovation, future income levels, demographic changes, human capital, etc. Surrogate indicators such as income, population, technology and governance are often used in the context of storyline development. As indicated above, storylines for low adaptive/mitigative capacity could combine assumptions such as high population growth, low income, relatively ineffective governance structures with slow technological change. This

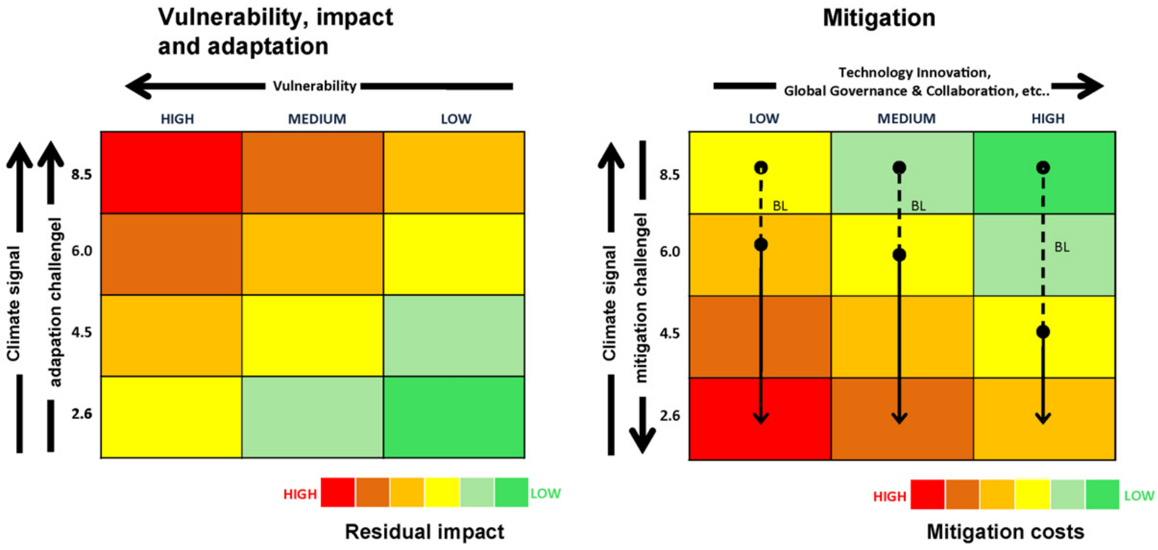

Fig. 7. Proposed framework with focus on the mitigation and 'vulnerability, impacts, and adaptation' dimension. The right-hand matrix gives in addition the potential range of baseline scenarios (dashed lines, BL) and the required mitigation effort to reduce the climate signal. The left hand matrix emphasizes the dependence on residual impacts on vulnerability. Note that the colours indicate possible outcomes in the framework (the scenarios are defined using the axis – not the colour coding). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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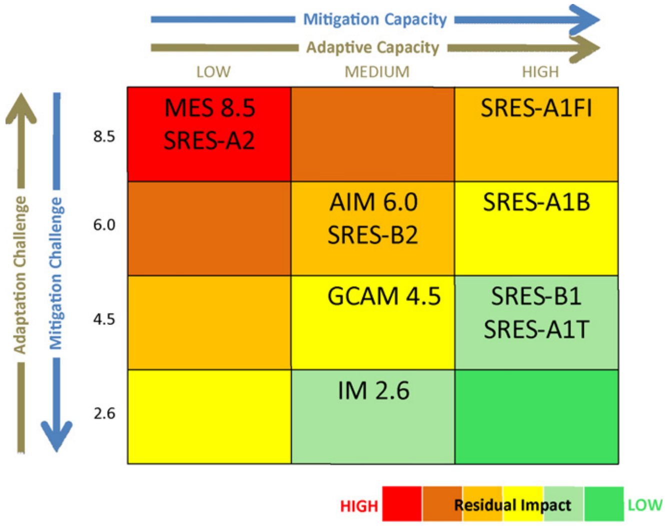

Fig. 8. The proposed framework compared to the SRES scenarios. The 4 scenarios underlying the RCPs and the IPCC scenarios have been added to the scheme to indicate how it can be used as heuristic to category scenarios.

coincides with the common archetype found in the literature of "regional competition" (or fragmentation) scenarios (e.g. A2 from the SRES set). In contrast, low population, high income, effective governance, and rapid technological change could form the backbone of assumptions for high adaptive and mitigative capacity - coinciding with the reformed market and sustainability scenarios in the archetypes (e.g. A1/B1). Intermediate assumptions about these factors could be used for the medium socio-economic development path and its storyline (e.g. B2).

Some aspects of this scenario matrix might be of higher relevance for different research communities. In Fig. 7, we further disentangle specific interpretations of the scenario framework for the impact and mitigation dimensions.

As illustrated, specifically for impact assessments the storylines will need to provide sufficient context to specify societies' vulnerability to climate change which is usually very much dependent on the local and regional context. A typical analysis could for example explore uncertainties of future impacts given a specific climate signal (or RCP level). The vulnerability might be explored as function of typical development parameters (e.g. economic growth) but also in terms of governance or preparedness to climate change (e.g. in developed countries to increased intensity of hurricanes or heatwaves). For this purpose "horizontal consistency" of providing contrasting socio-economic storylines that define alternative levels of vulnerability and adaptive capacity is of central importance.

On the other hand, "vertical consistency" might play a more important role for the typical mitigation analysis that would aim at understanding what it would take to reduce emissions and hence the climate signal from a high RCP level to a lower one. Such an analysis would need to be conditional on one single storyline (i.e. within a column) that provides sufficient information for defining a baseline for climate mitigation analysis. Thus, columns could be understood from the mitigation perspective as sets of different reference scenarios and mitigation counterparts to reduce emissions. Obviously, specific implications for mitigation costs or feasibility of low targets would be conditional on the specific column and its storyline. As illustrated in Fig. 7, mitigation costs are likely to be highest for socio-economic pathways that combine "low" assumptions about technology innovation, global governance and collaboration and thus have relatively lower mitigation capacity.

An important feature of the scenario framework is also that it provides a flexible taxonomy into which many earlier and present scenario assessments can be placed. Fig. 8 shows the relative position of the SRES and RCP socio-economic pathways within the matrix and the colour coding now corresponds to residual impacts. Similarly, also other scenarios such as those discussed in Table 2 could be placed into individual cells of the matrix according to the characteristics of their storylines (too some degree the assignment of the scenarios includes arbitrary decisions, as the columns have not been unambiguously defined yet). The framework thus provides thus not only a broader logic for how to pair socio-economic storylines with the RCPs, but also continuity and comparability with earlier important scenario assessments. As mentioned, this is really important as there continue to be many mitigation, impacts and adaptability studies across the world that are based on SRES. Fig. 8 also confirms our earlier conclusion that the RCP set does not cover the complete space of relevant scenarios for joint adaptation/mitigation analysis.

There are large differences between cells, in terms of storyline and most likely also probability. The upper left cell will suffer strong climate impacts (maybe beyond the current knowledge). The bottom left cell seems to be less probable as it combines a situation with low mitigative capacity with strong mitigation action. Similarly, also the upper right cell might be less likely as conditions for mitigation policy seem to be favorable.

Again, one should realize that the storylines are now defined at the global level. At the regional level, things may look very different (and different assumptions may be made within the overall framework).

5.2. Key issues for refining and applying the framework

Our intention in this paper was to provide an overarching logic for a scenario framework that would lead to the development of integrated scenarios for both the mitigation and the 'vulnerability, impacts, and adaptation' research. Many details of the framework still need to be scrutinized and several key questions will need to be addressed:

Number of columns. An open question is how many columns or storylines should be distinguished? At minimum one column is needed (intermediate assumptions). However, given the importance of comprehensive impact analysis for different levels of adaptive capacity and vulnerability, it would be more useful to consider at least two (high and low) or preferably three levels (low, intermediate, high) or even four levels (offering a symmetry to the four RCP levels).

Scenario characterization vs. marker scenarios. Another question is whether the framework is mostly used as a scenario heuristic – or whether for each column (or even each cell) specific "marker" scenarios are defined that are particularly representative of the type of scenarios within the framework. In the first case, existing scenarios from the literature would be qualified according to the framework. In fact, the scientific community would be encouraged to submit scenarios to populate the different cells within the framework based on simple criteria that define the columns/cells. In a subsequent step, it would be possible to analyze the scenarios typical for a certain cell. However, consistency across cells would be unlikely.

The second approach - use of one specific set for each column - would imply that different scenario assessments based on the framework would use the same internally consistent set of assumptions, and thus be better comparable and fully integrated. Obviously, not prescribing these sets would provide a higher level of flexibility. The two approaches are not mutually exclusive. For instance, SRES has used the concept of scenario families (covering a specific range of assumptions) with single representative marker

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scenarios for each family. A similar concept could be applied to the columns of our matrix. Given the importance of consistent analysis in the past, however, we feel that it would be helpful to provide such markers to the community. If such sets are not provided, indications of criteria of what “high GDP” constitutes would still provide a heuristic framework for communication.

Specification of the columns. It is an open question whether the columns would be defined in broad ranges (or criteria) for population, income and other variables or whether they would be defined more in qualitative scenario descriptions. Again, this choice is a trade-off between encouraging consistency across the scenario literature and allowing for flexibility – and again it might be possible to use the terminology defined by SRES (marker scenarios, harmonized scenarios and non-harmonized scenarios).

Origin of data. Should prescribed scenarios of socio-economic data based on existing model runs be used or should new, specifically designed scenarios be developed? Developing new sets of socio-economic assumptions provides the opportunity to use the most up-to-date information and expertise on population and income development (e.g. including the 2009/2010 economic and financial crisis). At the same time, existing scenarios, including the RCPs, might provide a good representation of the columns. However, again, consistency is an issue.

Consistency of socio-economic assumptions within a column or row. Are the socio-economic assumptions exactly the same within each column? At a minimum it seems desirable to retain “vertical consistency” by defining a baseline scenario for each column. This scenario could subsequently be used by a wide range of integrated assessment models for further mitigation analysis along each column. Developing the idea of marker scenarios from above further, it would be possible to use one storyline and a corresponding marker scenario from a specific integrated assessment modeling team as baseline for each column. Other teams could provide their interpretation of the same storylines within the column to depict uncertainty bands within each of the vertical cells.

But, vertical or column consistency alone means that scenarios are not comparable across rows. This will be particularly the case with regard to land use and land cover, where differences across models in their assumed terrestrial policies lead to differences that are potentially as large as that attributable to climate change. This loss in comparability could compromise the usefulness of the set of scenario framework. Theoretically, it would be possible for the community to select a single representative model for the purpose of developing a set that has full consistency across columns and rows. Of course, this leads to a crucial question how to weight scenario diversity and consistency across the rows.

Climate data. Similarly to different representation of futures by integrated assessment models, there are multiple climate models producing ensemble calculations. Without some guidance in selecting among possible future climate model runs comparability across climate impact studies could be compromised. Again, one may raise the question how to weight consistency (by using the output of a particular climate model) against uncertainty.

Scenario prioritization for ‘vulnerability, impacts, and adaptation’ analysis. To fully explore the range of possibilities captured by the proposed framework, twelve cells would have to be filled, while for each cell a variety of scenarios and scenario realizations using different models can be imagined. Such a large number of scenarios may not only be beyond the capability of the research community, it could also compromise policy relevance because of the associated complexity. Therefore, one may propose certain subset of cells within the framework as priority area for future assessments (Fig. 9). The priorities might differ for the impact and mitigation community – and also be depending on current knowledge. Focusing on the top-left and bottom-right corner of the matrix would provide an assessment of the full spread of impacts, while the other corners in the matrix would span the full range for mitigation costs. However, the feasibility and likelihood of some of these boxes are relevant questions. One crucial element here is whether there is a relationship between mitigative and adaptive capacity. Important future research may therefore focus on the question to which degree mitigative and adaptive capacity indeed co-vary, and under what circumstances we might expect them to converge/diverse. Adding the middle column could be used for exploring intermediate levels for either impacts or the mitigation effort. Together this would lead to a set of 6 priority scenarios in the framework. Similar to the work of the science community, other scenarios may be given a lower priority and might only be run in case a model group would have sufficient capacity. Prioritization clearly comes at a cost – as a full comparison cannot be made anymore. In that context, it clearly should be noted that the prioritization suggested in Fig. 9 is just a first proposal, as the downside of this proposal is the reduced comparison along the horizontal axis.

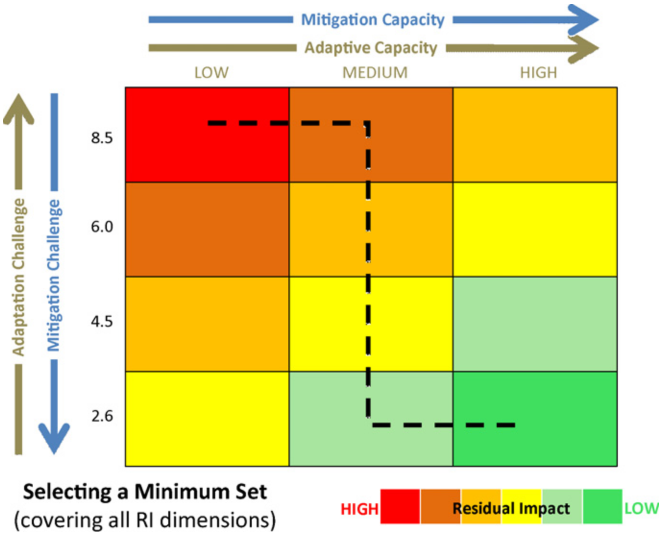

Fig. 9. The use of the proposed scenario framework to prioritize scenario analysis.

Time frame. Previous climate change scenario analyses have mostly focused on the long-term, notably a century timescale. This is useful, if not essential for long-term stabilization analyses, but less relevant from the perspective of short to medium term mitigation and adaptation analysis. It needs to be decided whether future socio-economic scenarios should more explicitly elaborate global and regional changes for at least the medium term (2–4 decades) in the context of century timescale scenarios.

6. Conclusions

This paper discussed how a framework for comprehensive impact and mitigation analysis can be defined consistent with the RCPs as organizing principle for the second step in the new process to develop scenarios for climate research (Moss et al., 2010). To do this, we have first defined a set of criteria for the scenario framework. Second, we have explored whether the socio-economic scenarios underlying the RCPs can be directly used to form a basis for the framework – or whether more work would be needed. This has led to five conclusions.

The first conclusion is that socio-economic scenarios underlying the RCPs are consistent sets of socio-economic assumptions for each RCP, but together they are not consistent and do not cover the full range of possible development pathways. The RCPs have been selected on the basis of their unique characteristics in terms of

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greenhouse gas emissions and concentrations. They were, however, not selected for their representation of the literature concerning socio-economic assumptions. Most of the RCPs represent the central part of the literature in terms of demographic and economic assumptions. Therefore, more work is needed if a scenario framework is to cover a wider range.

The second conclusion is that a broad set of socioeconomic projections can be consistent with a radiative forcing pathway. In the literature, there is very little correlation across the emissions scenarios between the individual assumptions for population and income and radiative forcing levels. As can be expected, other uncertainties are far more important for demographic and economic developments than climate policy. This implies that the RCP-forcing levels can be combined with a wide variety of assumptions. There are a few exceptions. For RCP8.5, there has to be a specific reason why radiative forcing is relatively high (low technology development, high coal use and/or high population levels). For RCP3-PD, there has to be strong climate policy – which implies that somehow conditions that allow strong climate policy need to be there.

A third conclusion is that a scenario framework has to be selective. It needs to make some assumptions to simplify the nearly infinite possible combinations of socio-economic assumptions at the global and local level. As shown in the literature review, there is a very wide range of combinations possible for different assumptions. Still in most assumptions only a limited set of scenarios are used and so some common archetype scenarios can be identified. Climate research should define a limited set of scenarios that directly target the main question of the analysis. This will require simplifications.

The new scenario process for climate research and assessment now calls for the development of a conceptual framework to provide an overarching logic for the development of socio-economic scenarios and their use in integrated mitigation and impact assessments. We believe that the framework, presented here provides a basis for doing so. We propose a set of scenarios which could provide a ‘‘thread’’ through the three climate research communities and which could provide a synthesizing framework. Our proposed set of scenarios are limited in size, comparable across scenarios, address a range in vulnerability characteristics, provide incremental information across climate forcing and vulnerability states and spans a full century in time scale. We propose the set of scenarios to be defined across two main axes. One is defined by the RCP radiative forcing levels (climate signal). The second axis is defined by socio-economic development – and comprises elements that affect the capacity for adaptation and mitigation but also system exposure to climate impacts. In the paper, we assumed that the second axis is continuous and that elements that determine adaptive and mitigative capacity correlate along this axis. This assumption, however, can be dropped in which case the second axis simply represents different, relevant, socio-economic conditions. We think that this framework would be useful for the identification of a limited set of scenarios that can be used as an analytical thread across a wide range of impact as well as mitigation assessments. Future scenario assessments based on the RCPs would therefore strengthen cooperation between integrated-assessment modelers, climate modelers and the impact community.

Finally, we propose that a process can be identified for scenario development on the basis of the proposed framework. This process consists of different steps in which the framework is first defined in terms of a minimum set of criteria. Next, scenario groups are invited to submit scenarios that fall into the framework. Within the framework we propose to select marker scenarios that can be used as illustrative examples of the scenarios in each cell/column. At the same time, these markers would be accompanied by a much broader set of scenarios. The creation of this set of scenarios that create threads will require new work by the integrated assessment modeling community in cooperation with the ‘vulnerability, impacts, and adaptation’ community. The detailed work plan remains to be crafted. But, the architecture, proposed in this paper, provides the foundation, upon which that plan could be built.

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