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SSP3: AIM implementation of Shared Socioeconomic Pathways

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ABSTRACT

This study quantifies the Shared Socioeconomic Pathways (SSPs) using AIM/CGE (Asia-Pacific Integrated Assessment/Computable General Equilibrium). SSP3 (regional rivalry) forms the main focus of the study, which is supposed to face high challenges both in mitigation and adaptation. The AIM model has been selected as the model to quantify the SSP3 marker scenario, a representative case illustrating a particular narrative. Multiple parameter assumptions in AIM/CGE were differentiated across the SSPs for quantification. We confirm that SSP3 quantitative scenarios outcomes are consistent with its narrative. Moreover, four key features of SSP3 are observed. First, as SSP3 was originally designed to contain a high level of challenges to mitigation, mitigation costs in SSP3 were relatively high. This results from the combination of high greenhouse gas emissions in the baseline (no climate mitigation policy) scenario and low mitigative capacity. Second, the climate forcing level in 2100 for the baseline scenarios of SSP3 was similar to that of SSP2, whereas CO_2 emissions in SSP3 are higher than those in SSP2. This is mainly due to high aerosol emissions in SSP3. A third feature was the high air pollutant emissions associated with weak implementation of air quality legislation and a high level of coal dependency. Fourth, forest area steadily decreases with a large expansion of cropland and pasture land. These characteristics indicate at least four potential uses for SSP3. First, SSP3 is useful for both IAM and impact, adaptation, vulnerability (IAV) analyses to present the worst-case scenario. Second, by comparing SSP2 and SSP3, IAV analyses can clarify the influences of socioeconomic elements under similar climatic conditions. Third, the high air pollutant emissions would be of interest to atmospheric chemistry climate modelers. Finally, in addition to climate change studies, many other environmental studies could benefit from the meaningful insights available from the large-scale land use change resulting in SSP3.

1. Introduction

The Special Report on Emissions Scenarios (SRES; Nakicenovic et al. (2000)) has been widely used in climate change research, not only for climate mitigation analysis but also for climate model (CM) simulations and climate change impact, adaptation, and vulnerability (IAV) assessments. Thousands of studies have discussed future climate change under the SRES scenarios and contributed to the fourth and fifth assessment reports of the Intergovernmental Panel on Climate Change (IPCC, 2007, 2014). Although SRES has succeeded in bridging gaps between different research communities, several issues still needed to be addressed (Moss et al., 2010). First, there is a high level of interest in climate scenarios that explore different approaches to mitigation in addition to the traditional no climate policy. Second, for CM and IAV analysis, more detailed emissions and socioeconomic scenarios along with higher resolution and more consistent land-use projections. Third, SRES was outdated and need to be updated by latest information. Forth, CM and IAV studies are time consuming, and certain mitigation scenarios have not been used in CM and IAV analyses based on SRES scenarios. To address these issues, a new scenario process (Moss et al., 2010), the so-called parallel approach, has been adopted, in which two sets of scenario developments are carried out in parallel. This process starts with the development of Representative Concentration Pathways (RCPs; van Vuuren et al. (2011a), and then climate and socioeconomic scenarios are developed in parallel. RCP development has been completed and summarized by van Vuuren et al. (2011a). The

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climate scenarios have also been finalized in the Coupled Model Intercomparison Project Phase 5 (CMIP5).

Shared Socioeconomic Pathways (SSPs) are designed to be used by multiple research communities to explore interactions between human societies and the natural environment throughout this century. Details of the concepts and structures of the scenarios are discussed by O'Neill et al. (2012), O'Neill et al. (2014), van Vuuren et al. (2013), and others. Similar to the SRES, SSPs contain both narratives and quantitative information. There are, however, at least four main differences between the SRES and SSPs. First, SSPs are characterized by a two-dimensional space in which the level of challenges to adaptation and mitigation are allocated, whereas SRES is described on the basis of the two-dimensional spaces of economic/environmental concerns and global/regional development patterns. Second, whereas SRES was designed with four main scenario families, there are five representative SSP scenarios. Four of them (SSP1, SSP3, SSP4, and SSP5) have various combinations of high or low levels of challenges to mitigation or adaptation, and the fifth (SSP2) has a medium level of challenges to both mitigation and adaptation (see Supporting information 1). Third, the SSPs were designed to be used in combination with a mitigation target (e.g., RCP levels), which is known as a scenario matrix approach, as described in van Vuuren et al. (2013). This approach enables IAV studies to conduct assessments, including mitigation scenarios, which is a unique characteristic and is not possible with the SRES. For example, under the same stringent climate target, the effect of different socioeconomic assumptions can be investigated. Although post-SRES studies have dealt with mitigation (Morita and Robinson, 2001), these scenarios have not been used either in CM or in IAV research. Fourth, the base year of the SSP scenarios is 2005 whereas SRES has a base year of 1990.

Six Integrated Assessment Models (IAMs) are used to quantify the five SSPs: AIM (Asia Pacific Integrated Model; Fujimori et al. (2014c)), GCAM (Global Change Assessment Model; Calvin (2017)), IMAGE (Integrated Model to Assess the Greenhouse Effect; Detlef P. van Vuuren (2017)), MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact; Fricko et al. (2017)), REMIND-MAgPIE (Regionalized Model of Investments and Development-The Model of Agricultural Production and its Impact on the Environment; Kriegler (2017)), and WITCH (World Induced Technical Change Hybrid model; Bosetti et al. (2011)). We have been developing AIM and it has also been used to contribute to the development of various international scenarios, including SRES, Millennium Ecosystem Assessment Reports and RCPs (Alcamo et al., 2005; Masui et al., 2011; Nakicenovic et al., 2000). Six modeling teams have attempted to quantify either part or all of the SSPs. The marker scenarios, which are representative scenarios used to illustrate a particular narrative in the IAMs involved in the SSP quantification process for each SSP, are selected from the six scenarios used by the modeling team. AIM has been appointed for quantification of the SSP3 marker scenario.

Given this background, this study has three objectives. The first is to explore the results of SSP3 quantified using AIM. The second is to present concrete model parameter assumptions for SSP quantification. The third is to evaluate whether the quantitative scenarios are consistent with the narrative. To meet the first objective, we investigated the primary energy supply, greenhouse gas (GHG) emissions, air pollutant emissions, land use, and climate information. For the second, we listed all assumptions that characterize the narrative of each SSP. With respect to the third objective, even though the parameters are assumed to be generating the SSPs' characteristics, it is not necessarily the case that the model outcomes are consistent with the narratives. To check the consistency of narratives and quantitative scenarios, we proposed several criteria. Although there are many potential indicators that could be evaluated, we limited the analysis to the macro-level aggregated indicators, because our aim was to show the basic nature of the quantified SSPs rather than the detailed indicators.

This paper is organized as follows. Section 2 presents the overall methodology, model, scenario framework, and data settings, and Section 3 shows the results of the analysis. Because the paper length is limited, we discuss three scenarios. The main focus of this paper is SSP3 but SSP1 and SSP2 have been selected for comparison. SSP2 is the middle-of-the-road scenario which is interpreted as historical extension and appropriate to compare as the reference. From the perspective of SSP2, SSP1 (low) sits in direct opposition to SSP3 (high) in the context of challenges to mitigation and adaptation. Therefore, knowing the position of SSP3 relative to SSP1 and SSP2 may aid understanding of the characteristics of SSP3. If we chose SSP4 or SSP5 instead of SSP1, the SSP3 characteristics in either mitigation or adaptation would be unclear. In Section 4, we interpret the results, make recommendations for the usage of SSP3, and discuss the limitations of the study. Concluding remarks are provided in Section 5.

2. Methodology

2.1. Overview of the method

AIM/CGE (Computable General Equilibrium) was used for quantification of the SSPs, which has been widely applied for the assessment of global and national climate mitigation analysis (e.g., (Fujimori et al., 2014b; Fujimori et al., 2013, 2015; Hasegawa et al., 2016; Hasegawa et al., 2015a; Namazu et al., 2013; Thepkhun et al., 2013). The period from 2005 to 2100 was targeted. MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change) version 6 (downloaded in August 2014 with some parameters were adjusted to reflect CMIP5 results) was used to compute climate information such as global mean temperature change and radiative forcing (Meinshausen et al., 2011). Following van Vuuren et al. (2013), a scenario matrix approach was used in two dimensions to assess possible combinations of socioeconomic assumptions and climate targets, which are discussed in Section 2.3. To quantify mitigation scenarios, both radiative forcing targets and climate policy variations were considered, as discussed in Section 2.4.

2.2. AIM/CGE basic model structure

Version 2.0 of the AIM/CGE model was used in this study (version 1.0 was used by Masui et al. (2011)); this is a one-year-step recursive-type dynamic general equilibrium model that covers all regions of the world. The AIM/CGE model includes 17 regions and 42 industrial classifications (see Supporting information 2 for the regions and industries). For appropriate assessment of bioenergy and land use competition, agricultural sectors are also highly disaggregated (Fujimori et al., 2014a). Details of the model structure and mathematical formulae are described by Fujimori et al. (2012).

The production sectors are assumed to maximize profits under multi-nested constant elasticity substitution (CES) functions and each input price. Energy transformation sectors input energy and value added are fixed coefficients of output. They are treated in this manner to deal with energy conversion efficiency appropriately in the energy transformation sectors. Power generation values from several energy sources are combined with a Logit function (Sands, 2004). This functional form was used to ensure energy balance because the CES function does not guarantee an energy balance. Household expenditures on each commodity are described by a linear expenditure system function. The parameters adopted in the linear expenditure system function are recursively updated in accordance with income elasticity assumptions. The saving ratio is endogenously determined to balance saving and investment, and capital formation for each good is determined by a fixed coefficient. The Armington assumption is used for trade (CES and constant elasticity of transformation function is used), and the current account is assumed to be balanced.

In addition to energy-related CO_2, CO_2 from other sources, CH_4, N_2O, and fluorinated gases (F-gases) are treated as GHGs in the model. Energy-related emissions are associated with fossil fuel feedstock use. The non-energy-related CO_2 emissions consist of land use change and industrial processes. Land use change emissions are derived from the forest area change relative to the previous year multiplied by the carbon stock density, which is differentiated by AEZs (Global Agro-Ecological Zones). Non-energy-related emissions other than land use change emissions are assumed to be in proportion to the level of each activity (such as output). CH_4 has a range of sources, mainly the rice production, livestock, fossil fuel mining, and waste management sectors. N_2O is emitted as a result of fertilizer application and livestock manure management, and by the chemical industry. F-gases are emitted mainly from refrigerants used in air conditioners and cooling devices in industry.

Air pollutant gases (BC, CO, NH_3, NMVOC, NO_X, OC, SO_2) are also associated with fuel combustion and activity levels. Essentially, emissions factors change over time with the implementation of air pollutant removal technologies and relevant legislation.

The implementation of mitigation actions in the model is represented by assuming either a global Kyoto gases total emissions constraint or a GHG emission price path. These two methods are adopted depending on Shared Policy Assumptions (SPAs), which are explained in Section 2.4 and Supporting information 3. For SPA0 and SPA1 policy cases, GHG emissions caps are assumed. They are derived from RCPs by using 100-year global warming potential information from the IPCC fourth assessment report. For SPA2 to SPA5, the carbon price path is assumed. It is derived from the SPA1 results (e.g. the carbon price in SPA3 is twice as much as in SPA1). Once the emission constraint is implemented, the carbon price becomes a complementary variable to that constraint, and determines the marginal mitigation cost. This GHG emission price is assumed in the model as a GHG emission tax, which makes the price of fossil fuel goods higher when emissions are constrained and promotes energy savings and substitution away from fossil fuels to lower GHG emission sources and carriers. The GHG emission tax also acts as an incentive to reduce non-energy-related emissions. Gases other than CO_2 are weighted by global warming potential and summed as total GHG emissions. Households are assumed to receive revenue from GHG emissions taxes as a lump-sum transfer from the government.

2.3. Scenario framework

The two dimensions of the scenario framework are socioeconomic conditions and climate conditions, as shown in Fig. 1. The socioeconomic dimension includes the five SSPs, and assumptions about demography, economy, energy, agriculture, land use and air pollutant legislation are differentiated among the SSPs. The climate condition dimension includes climate mitigation targets and the baseline case. The baseline case does not include a climate mitigation policy. Climate conditions are represented by four RCP levels (2.6, 4.5, 6.0 and 8.5 W/m^2), and two additional forcing levels (3.4 and 7.0 W/m^2). The case with a forcing level of 7.0W/m^2 roughly corresponds to the SSP2 and SSP3 baseline cases. The 3.4 W/m^2 stabilization case has been commonly used in various earlier mitigation studies and has a high level of policy relevance

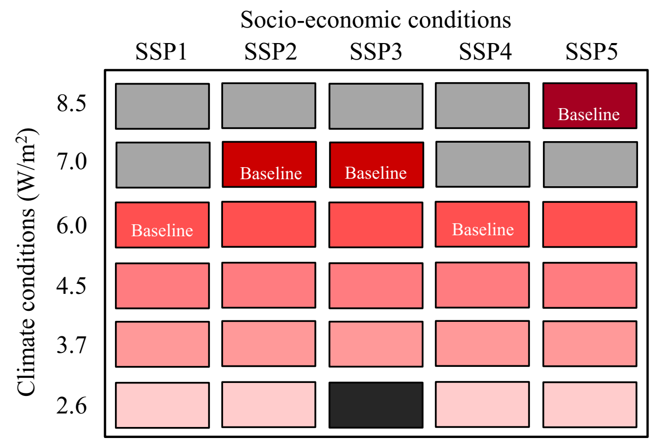

Fig. 1. Scenario framework.

(Clarke et al., 2014). Therefore, these two forcing levels were added to the RCPs. Each combination of socioeconomic and climate target conditions is denoted as, for example, SSP3-BL and SSP3-3.4W. In Fig. 1, the gray areas indicate either incompatible or not being generated in this study. SSP1-4 are because their radiative forcing are over the corresponding baseline scenarios. SSP5-7.0W is a possible combination, but this forcing level would be too high to be a realistic mitigation target in the context of current policy decisions. It was also infeasible to obtain a solution for the SSP3-2.6W scenario (black box in Fig. 1), given that the challenges to mitigation at that level in SSP3 are too great, at least in AIM implementation.

Climate conditions correpond to RCPs plus 3.4 and 7.0W/m^2 forcing levels in 2100. Top grey areas except for SSP5-7.0W are not available because baseline scenarios are below the forcing levels. SSP5-7.0W would not be a viable mitigation target in the context of policy decisions, and was omitted from the study. Reaching the 2.6 W/m^2 level from the SSP3 baseline (SSP3-2.6; black area) was found not possible. This figure is based on Fig. 1 in van Vuuren et al. (2013)

2.4. Climate mitigation policy

The SPA concept explained by Kriegler et al. (2014) is adopted for the mitigation scenarios. The implementation protocol is described in (Riahi et al., 2015) and only a brief description is offered here. SPAs consist of assumptions of regional and sectoral coverage for participation in climate mitigation. In other words, SPAs specify who will face the carbon price. The ideal situation is that all regions and sectors work cooperatively to reduce their emissions, while cases that are worse limit participation of either sectors or regions. Six policy assumptions, namely SPA0 to SPA5 were defined. SPA0 is the ideal case as described above, where mitigation starts immediately (actual model implementation is from the year 2015). SPA1 is not the best but also not the worst case; mitigation is fragmented across countries until 2020 in a way consistent with Cancun pledges, but all regions and sectors join in mitigation activities thereafter. In terms of regions, SPA2, SPA4, and SPA5 share the same participation rule in which all high-income countries will fully participate in mitigation after 2020. Low-income countries, however, will start mitigation efforts in 2030 and reach the same global GHG emission price in 2040. SPA3 assumes the most regionally fragmented case where high- and low- income countries gradually start to participate in beginning of 2020 and 2030, respectively; the high- and low- income countries reach global GHG emission price convergence in 2040 and 2050, respectively.

In terms of sectoral coverage, reductions in land-use and agriculturally-related emissions are differentiated between the SPAs. SPA0 and SPA1 fully cover those sectors. SPA3 and SPA4 have limited coverage (i.e., have low pricing on their emissions). SPA2 is in the middle of these two extremes. Each SPA was paired with its corresponding SSP that is, SSP1-SPA1, SSP2-SPA2, and so on (the reasons for doing so are discussed in Section 4.2). The actual methodology of implementing the SPAs within the AIM/CGE framework is described in Supporting information 3.

2.5. Evaluating model outcomes

As discussed in the introduction, one of the primary objectives of this study was to evaluate the quantified SSPs in terms of their consistency with their narratives. Several criteria can be used for evaluation of the general outcomes of IAMs (Schwanitz, 2013). Various aspects of the general narrative of SSPs are directly stated (O'Neill et al., 2017), however, some of them are difficult to compare directly with IAM outcomes. To meet our objectives, indicators of the narratives that could be compared with IAM outcomes were selected.

Three main points need to be evaluated in the context of consistency, particularly when characterizing SSP3. First, the most fundamental feature is the degree of challenge to mitigation. SSP3 is supposed to have a high degree of challenge, defined as "consisting of: (1) factors that tend to lead to high baseline emissions in the absence of climate policy . . . ; and (2) factors that would tend to reduce the inherent mitigative capacity of a society" (O'Neill et al., 2017). The factors in (1) should be checked in the parameter assumptions (e.g., population, GDP, energy intensity improvement, land regulation and so on) and the baseline case GHG emissions. The factors related to (2) can also be addressed in the parameter assumptions (e.g., high cost in reducing emissions). Moreover, mitigation cost measures are appropriate indicators to represent these factors. Second, "regional rivalry" is another important symbolic key word representing SSP3 (O'Neill et al., 2017) (e.g.; for SSP3; which refers to the grade of openness or protectionism of countries in terms of trade.). Within this context; we evaluated trade dependency (import ratio to domestic consumption). Third; O'Neill et al. (2017) state that; in SSP3; "Investments in education and technological development decline. Economic development is slow." Demography and Economic development is an exogenous assumption from Kc and Lutz (2017) and Dellink et al. (2017) for AIM/CGE such that slow economic development is already reflected in that assumption (see Section 2.6.1 for a more detailed discussion of this topic). The other specific technological aspects are energy and agricultural technologies. We make the interpretation that energy and carbon intensity improvement rates are represented in energy-related technologies and yield growth rates are represented in agricultural technology. IAMs basically capture mitigation aspects in detail; but there is no explicit description of the adaptation side; with some exceptions; such as agricultural sectoral behaviors. Thus; in this paper we focus on the consistency of the mitigation side.

2.6. Data and future scenario parameter settings

2.6.1. Parameter assumptions for scenario quantification

There are multiple parameters in the model to characterize each SSP that needs to be differentiated. A full list of the assumptions and individual SSP parameterization schemes are shown in Table A.1. Demographic information is totally exogenous to the model. Demographic and macro-economic data are based on Dellink et al. (2017); Kc and Lutz (2017) (The overall figures are shown in Supporting information with regional breakdown). Although conventional CGE models approach total factor productivity (TFP) as an exogenous assumption, this treatment includes the possibility of having different GDP outcomes. Therefore, in this SSP quantification, we adjusted the TFPs of the baseline scenarios as an adjustment variable to obtain exactly the same GDP outcomes as assumed. The calculated TFPs in baseline scenarios are then applied to the mitigation scenarios. The outcomes in TFP are shown in Supporting information SI Fig. 4. The order of SSPs in TFP is normally SSP1, SSP2 and SSP3 but varies across regions.

The basic strategy for the remainder of the parameterization of each SSP assumption follows three steps. First, SSP2 assumptions are determined to reflect the historical or current situation (including policies such as air pollutant legislation). Second, the direction of each parameter for the other SSPs relative to that of SSP2 is assumed based on either an SSP quantification protocol (Riahi et al., 2015) or the narratives. Third, actual parameter assumptions are made to construct a wide range of plausible scenarios. An important fact to note here is that the actual parameter numbers chosen for the individual SSPs in this study may be different between different modelers, as discussed by Hasegawa et al. (2015b). This point is discussed in more detail in Section 4.

2.6.2. Base year data

CGE models generally use a Social Accounting Matrix (SAM) to calibrate the model parameters. To assess energy flow and GHG emissions more precisely and more realistically, the CGE model should account not only for the original SAM but also for energy statistics. The Global Trade Analysis Project (GTAP) (Dimaranan, 2006) and energy balance tables (International Energy Agency, 2013a,b) were used as a basis for the SAM and energy balance table, and data were reconciled with other international statistics such as national account statistics (United Nations, 2013). The concept behind the reconciliation method is described by Fujimori and Matsuoka (2011). GHG and air pollutant emissions were calibrated to EDGAR4.2 (EC-JRC/PBL, 2012). For the land use and agriculture sectors, agricultural statistics (Food and Agriculture Organization of the United Nations, 2013), land use RCP data (Hurtt et al., 2011), and GTAP data (Avetisyan et al., 2011) were used for physical data.

2.6.3. Other data for future scenarios

Solar and wind resource energy potential are adopted from Silva Herran et al., 2016, which computed these potentials on the basis of high spatial resolution data (0.5 arc-minute or ~1 km at the equator). Fossil fuel resources are based on Rogner (1997). F-gas emissions are exogenously determined using the method described by Harnisch et al. (2009).

3. Results

3.1. Primary energy

Fig. 2 illustrates total energy supply and energy sources for the baseline (time series) and other climate policy cases in 2100. In the baseline case, the total energy supply of SSP3-BL is slightly higher than that of SSP2-BL, which reaches about 1274 EJ/year in 2100. SSP1-BL has a different trend, particularly in the latter half of the century. Total supply declines after 2070, reaching 573 EJ/year in 2100. The compositions of the energy sources are different in SSP2-BL and SSP3-BL. SSP3-BL shows a fossil fuel dependent,more specifically coal oriented development, reflected in the higher coal consumption levels in SSP3-BL: for example, consumption in the year 2100 was 589 EJ/year, and 363 EJ/year in SSP3-BL and SSP2-BL, respectively. In the narrative, SSP3 is described as high fossil fuel dependent world and the result is consistent with that. Although it

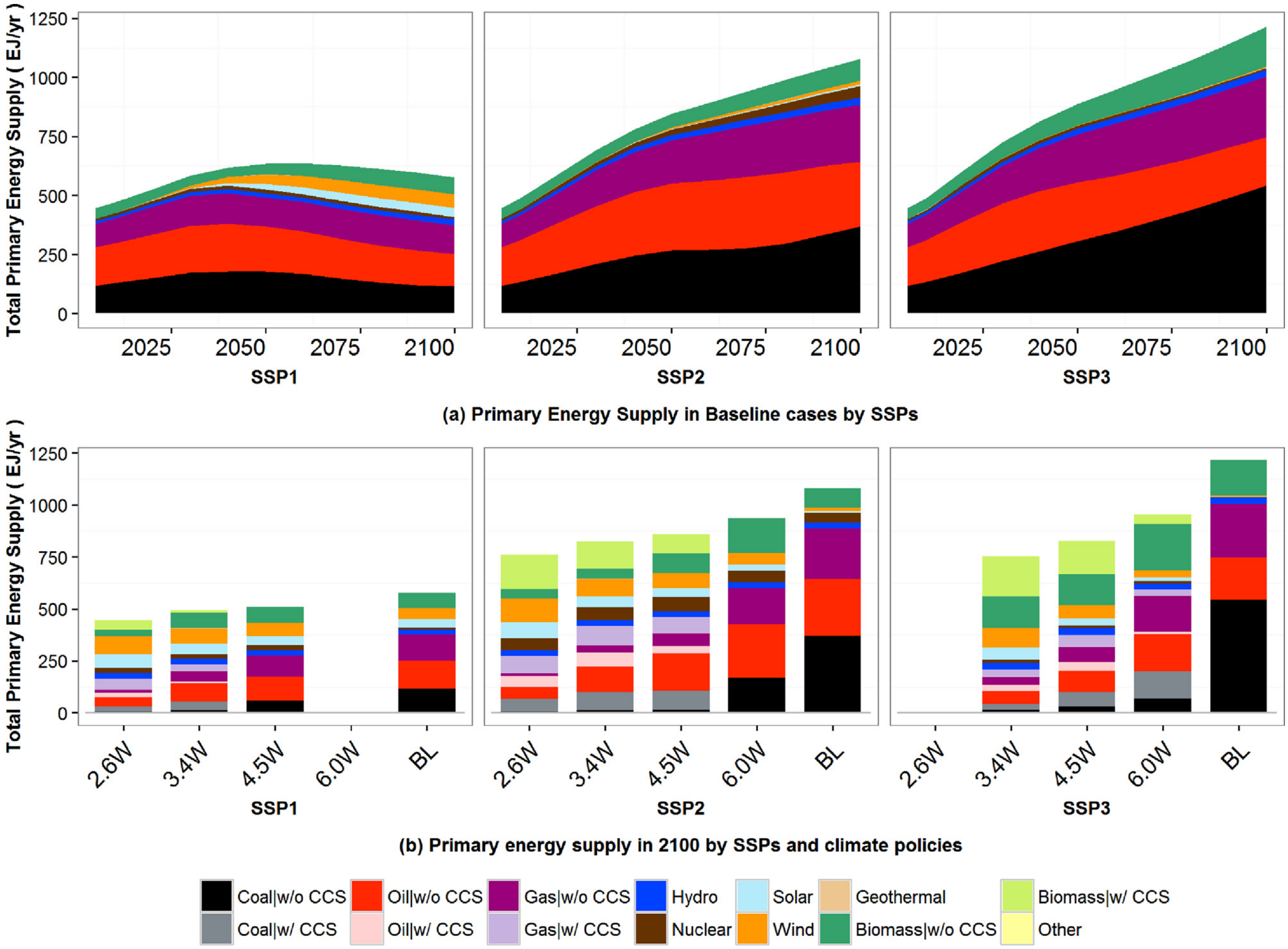

Fig. 2. Global primary energy supply and energy sources associated with the baseline (top) and other climate policy cases in 2100 (bottom) for SSP1, SSP2 and SSP3.

is not quite as marked as with coal, there is also a large difference in nuclear energy production between SSP2-BL and SSP3-BL. Nuclear technology development is slower in SSP3-BL (as assumed in Table A.1), and SSP3 has a smaller share of nuclear energy in 2100 than SSP2. The nuclear power in SSP1-BL declines since its social acceptance is low in SSP1. In comparison with SSP3-BL, SSP1-BL has an increasing share of renewable energies, and a decreasing energy supply from fossil fuels, particularly coal. This SSP1-BL trend is consistent with the narrative characterized as sustainability. Regarding regional breakdown, SSP3-BL energy increase is mainly driven by low income regions where they have relatively large population increase and slow energy efficiency improvement such as Asia and Africa (Supporting information SI Fig. 5).

Focusing on the mitigation cases, a stronger mitigation level leads to decrease in total energy supply. There are three factors behind this trend. First, final energy consumption (see Supporting information SI Fig. 6) decreases through energy saving due to the high carbon price. For example, final energy consumption of SSP3-3.4W in 2100 shows a 30% decrease from that of SSP3-BL. On the other hand, SSP1 shows only 10% decrease in final energy consumotion in SSP1-34W because SSP1 has high mitigation capacity and low carbon price. Second, the shift from fossil fuel fired power to renewable energies in the power supply system would increase the primary energy efficiency. The efficiency in fossil fuel fired power is typically less than 50% whereas that in renewables like solar and wind is accounted as 100%. Third, macroeconomic losses caused by the mitigation efforts reduce the driving force of energy consumption.

Regarding energy composite, the stronger mitigation level, more renewable energy and carbon capture and storage (CCS) are used. The coal and oil greatly decrease even in 6.0W or 4.5W cases. This tendency is commonly seen in all SSPs. Regarding SSP3 scenarios, large amount of biomass is remarkable. This is dues to the high social acceptance in modern bioenergy use and limited technology progress in other renewable energies. Comparing SSP3-3.4W and SSP2-3.4W (3.4W stabilization is the most stringent climate policy case for SSP3), the compositions of energy sources are substantially different though their total energy supply are almost same. SSP3-3.4W requires a greater reduction in fossil fuel energy supply than SSP2-3.4W, so the share of fossil fuel is much smaller in SSP3-3.4W. One reason for this difference is that the amount of non-CO_2 emissions in the baseline scenario varies, as does their reduction potential in the mitigation scenarios. The SSP3 baseline scenario has a higher level of non- CO_2 emissions than the SSP2 baseline scenario due to high population (high emissions in agricultural CH_4 and N_2O), and also has less potential for emission reduction in the mitigation scenario because of this assumption (Fig. 2). This implies that CO_2 emissions need to be reduced more in SSP3 than in SSP2, and that the energy system in SSP3 must change significantly. In contrast, SSP1 already has reduced fossil fuel dependency in the baseline scenario, and the mitigation scenario is rather similar to the baseline one.

3.2. Land use

Land use is one of the core variables in the SSPs, particularly for the IAV community. Fig. 3 shows the results for three main land-use variables, specifically, cropland, forestland, and pasture land. The basic features of the baseline case for SSP3-BL are a high deforestation rate and large expansions of cropland and pasture land, as compared to both the SSP1-BL and SSP2-BL cases. In the baseline case, the areas of cropland and pasture land in SSP3-BL in 2100 increase to 2293 Mha and 3705 Mha, respectively, which constitute increases of 40% and 20% from the base year. The main driver of these increases is the combination of large population increases, slow yield growth rates, and low intensification of the livestock system. The population almost doubles from 6.5 billion in 2005–12 billion in 2100, but the yield growth rate is very slow as assumed. Fig. 4 presents 10-year mean annual yield growth rates for the three SSPs along with the historical pattern since 1960. In the 1960s, the so-called green revolution brought very rapid yield growth. Since then, the yield growth rate has declined and the future scenarios reflect this trend. SSP3-BL, however, has a much lower yield growth rate, as compared to the other SSPs; the mean annual growth rate over the study period is about 0.3% for SSP3-BL, whereas the rates for SSP1-BL and SSP2-BL are 0.6% and 0.4%, respectively. Even larger differences can be seen in the first half of the century, when the mean annual yield growth rates for SSP3-BL, SSP1-BL, and SSP2-BL are 0.5%, 0.9%, and 0.7%, respectively. In the latter half of this century, there are small rebounds for which there are two possible reasons. One is the regional composition change.

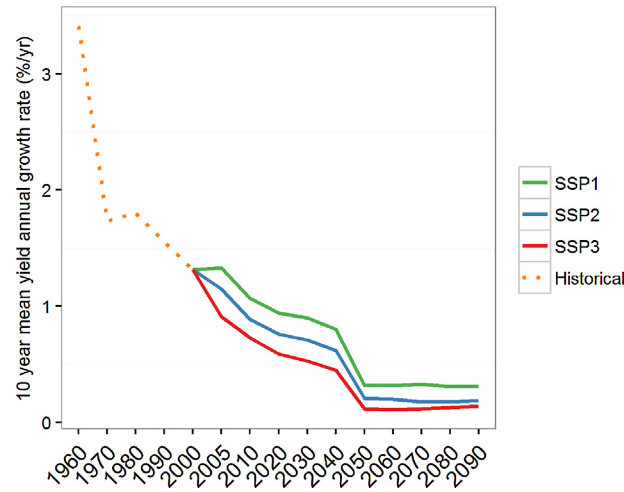

Fig. 4. Ten-year mean annual yield growth rate for the SSP1, SSP2, and SSP3 baseline scenarios. The x-axis represents each decadal period (i.e., 1960 means the 1960s).

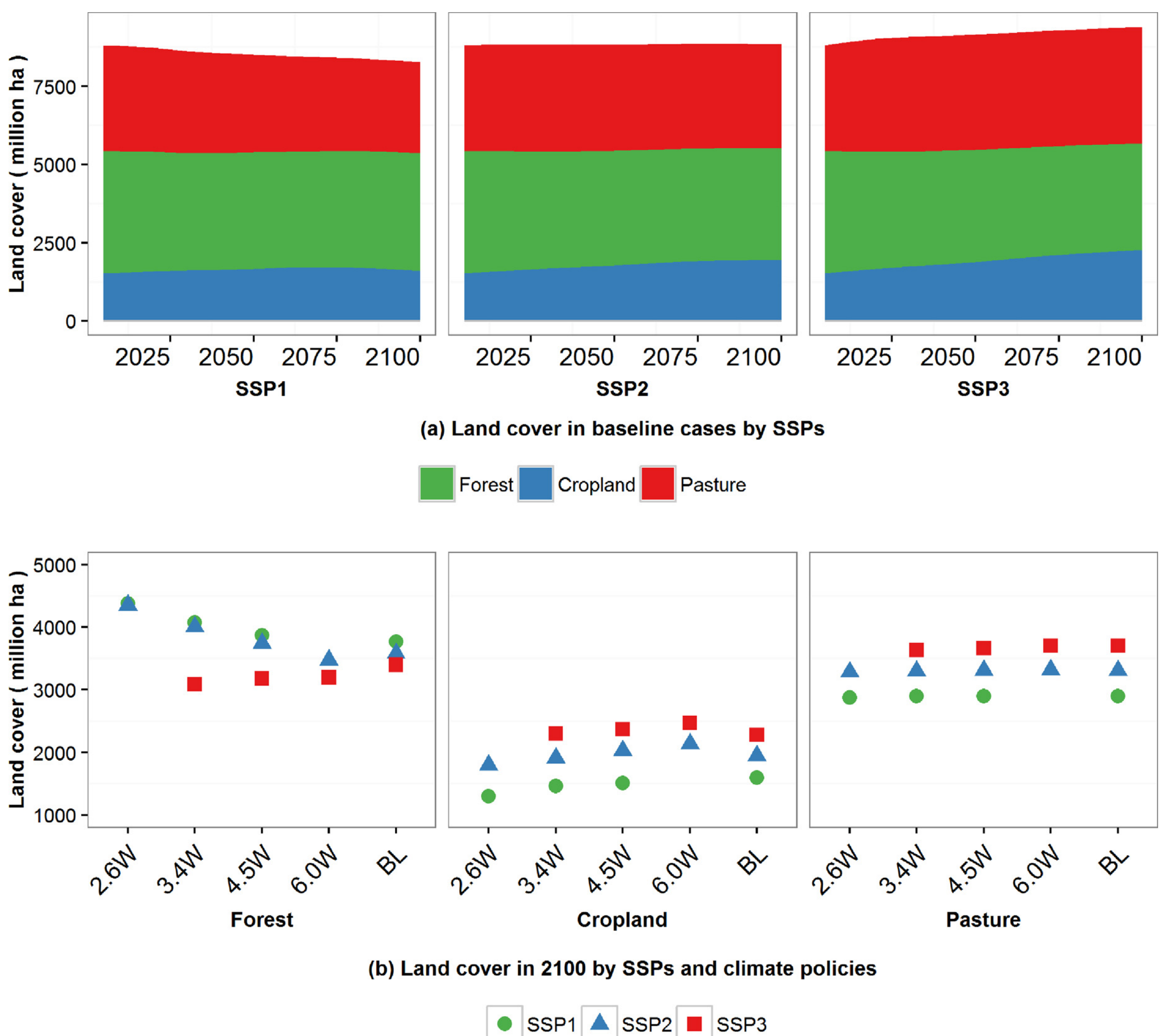

Fig. 3. Global land-use area for (a) baseline time series and (b) mitigation cases in 2100 for SSP1, SSP2, and SSP3.

The share of regions having high yield such as Africa and South Asia increases (Supporting information SI Fig. 7). The other is the price effect. Increases in agricultural price cause increase in yield.

Land use in SSP3 is also different from the other SSPs in the mitigation scenarios. While the forest area increases and cropland decreases in SSP2 as a result of climate mitigation, neither of these trends is evident in SSP3. This is mainly a result of the possibility of afforestation in SSP2 because it enables carbon pricing for forest and soil carbon stocks, and afforestation will be enhanced by climate mitigation. Conversely, SSP3 is assumed to have low carbon pricing for land emissions so that forest area will not be affected to the same degree in this scenario. The trends for SSP1 are similar to those for SSP2 because the SPA assumptions for the land-use sector for SSP1 and SSP2 are similar.

3.3. GHG emissions

Fig. 5 illustrates global GHG (Kyoto gases) emissions and their compositions for major gases (CO_2, CH_4 and N_2O). Total GHG emissions for the SSP1 -BL, SSP2-BL, and SSP3-BL cases are 49, 95, and 117 $GtCO_2eq$/year in 2100, respectively. SSP2 and SSP3 constantly increase throughout this century while SSP1-BL peaks around 2050 and decline. From the short to the long term, SSP3-BL has a consistently higher emissions trajectory. In the mitigation scenarios, however, there are only small differences between SSP1, SSP2, and SSP3 in 2100. The most apparent differences can be seen in the medium-term emissions trajectory for all mitigation scenarios. SSP3 has higher emissions between about 2030 and 2040, because the underlying SPA assumes that SSP3-SPA3 has the most fragmented climate mitigation policy, and 2030 is the year when developing countries start to participate in the climate policy. Therefore, after all countries have joined in mitigation efforts and the GHG emissions price reaches convergence in 2050, emissions are immediately and significantly reduced. In contrast, SSP2-SPA2 assumes GHG emission price convergence in 2040 (developing countries start to reduce their emissions in 2020), and SSP1-SPA1 assumes all countries participate in climate mitigation equally in 2020. As a result, short- and medium-term emissions are lowest in SSP1. SSP2-2.6W and SSP3-3.4W have negative emissions of CO_2 and they reach zero CO_2 emissions around 2070 and 2090 respectively. Eventually, in 2100, they show 3 and 4 $GtCO_2$ negative emissions. SSP1-2.6W does not have negative emissions in global total because the biomass with CCS does not increase so much due to the low social acceptability in CCS. Non-CO_2 emissions in SSP1

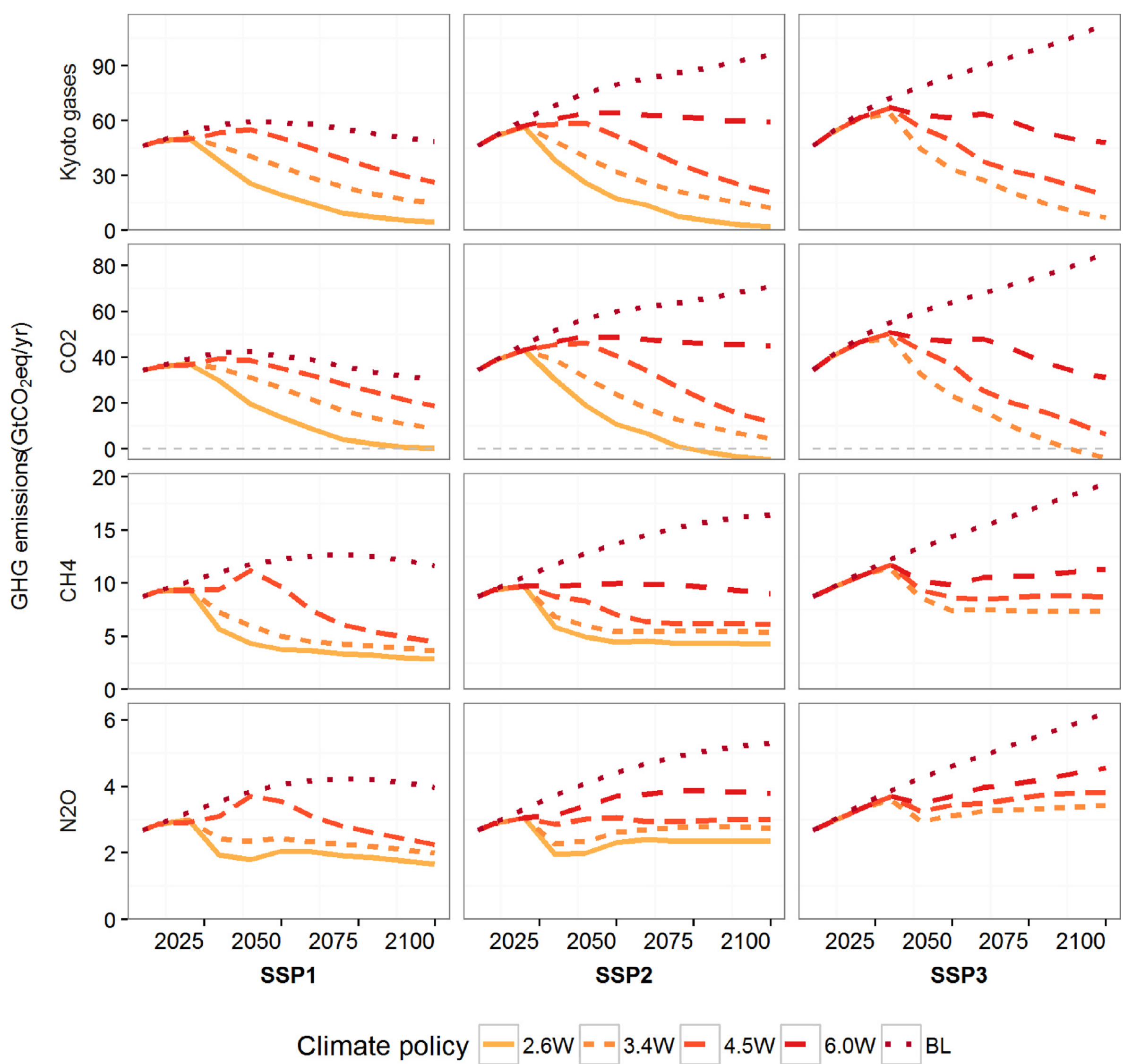

Fig. 5. Global GHG, CO_2, CH_4, and N_2O emissions (from top to bottom) associated with the five mitigation cases for SSP1, SSP2, and SSP3.

are less than those in SSP2 and SSP3. Therefore, the CO_2 emission in SSP1 does not need to be as low as in other scenarios. For the SSP3-3.4W, even though the climate target is more modest than SSP2-2.6W, it has similar negative emissions in 2100. This is because SSP3 has larger non-CO_2 emissions than SSP2 and less GHG emissions budget is left for CO_2.

Similar trends were observed with CO_2 emissions, although the differences in emissions in 2100 between SSP2 and SSP3 are more clearly visible than for total GHG emissions, with SSP3 having lower emissions in mitigation cases. Two factors contribute to these results. One is the previously discussed non-CO_2 emissions trajectories, where non-CO_2 gas emissions in SSP3 are higher than in SSP2, so CO_2 emissions must be reduced even further. The other factor is that SSP3 has higher near- and medium-term emissions, which implies that emissions in the latter part of the century need greater reductions to reach a similar level of forcing in 2100. CO_2 emissions in SSP1 are basically a little higher than those in SSP2, indicating that SSP1 has lower non-CO_2 emissions, and that CO_2 emissions do not need to be reduced as sharply.

Non-CO_2 emissions have one important characteristic that differs from CO_2 emissions. Net CO_2 emissions can be negative through the incorporation of bioenergy combined with CCS or afforestation, whereas there are no equivalent countermeasures for non- CO_2 emissions. Moreover, the reduction potential is limited for non-CO_2 emissions. Therefore, all non-CO_2 emissions figures show an unavoidable minimum level of emissions, even in the most stringent climate mitigation scenarios (e.g., 2.6W). Nevertheless, emissions in the baseline scenarios mostly increase throughout the period, so the rate of reduction is higher as time passes. The sectoral breakdown of the non-CO_2 emissions indicates that a large part of CH_4 from enteric fermentation and N_2O from agricultural waste management remains even in the stringent climate policy cases for all SSPs (ses Supporting information SI Figs. 8 and 9).

3.4. Air pollutant emissions

Fig. 6 illustrates selected global air pollutant (NO_x and SO_2) emissions for SSP1, SSP2, and SSP3. Overall SSP3-BL air pollutant emissions are stable or show modest reductions in this century in the baseline scenario. They are higher than SSP2-BL emissions, and furthermore, air pollutant emissions in SSP3-BL are the highest of all the SSPs in the baseline scenario (Supporting information 4). For example, SSP3-BL NO_x and SO_2 emissions in 2100 are 116 $MtNO_2$/year and 86 $MtSO_2$/year respectively, whereas the corresponding values for SSP2-BL are 57 $MtNO_2$/year and 25 $MtSO_2$/year. The corresponding values are even lower for SSP1-BL at 26 $MtNO_2$/year and 9 $MtSO_2$/year, respectively. The combination of the worst air pollution legislation assumptions, where only the current legislation is realized in the latter half of this century, and the continued dependence on fossil fuels (particularly coal) in SSP3 is primarily responsible for these characteristics.

The decomposition analysis for the NOx and SO_2 are carried out and the outcomes are shown in Fig. 7. We observed that there are common trends where the GDP per capita is always a positive factor while the emission intensity is a negative factor. SSP1 and SSP2 have continuous energy intensity improvement, but SSP3 does not. The magnitude of these factors is different across SSPs. SSP3 has very slow improvement speed in both emission and energy intensity, whereas SSP1 shows rapid improvement. The differences in emissions intensity improvement speed among SSPs are more obvious in the former part of century.

In the mitigation scenarios, they drastically decrease, as compared to the baseline scenarios in all SSPs. A primary reason for this is that of the major sources of each pollutant. The emissions of SO_2 and NO_x gases are directly related to fossil fuel combustion. These emissions can easily be reduced or eliminated by either changing the energy source structure from coal to other low carbon fuels, including renewable energy, or by including CCS. SO_2 is the

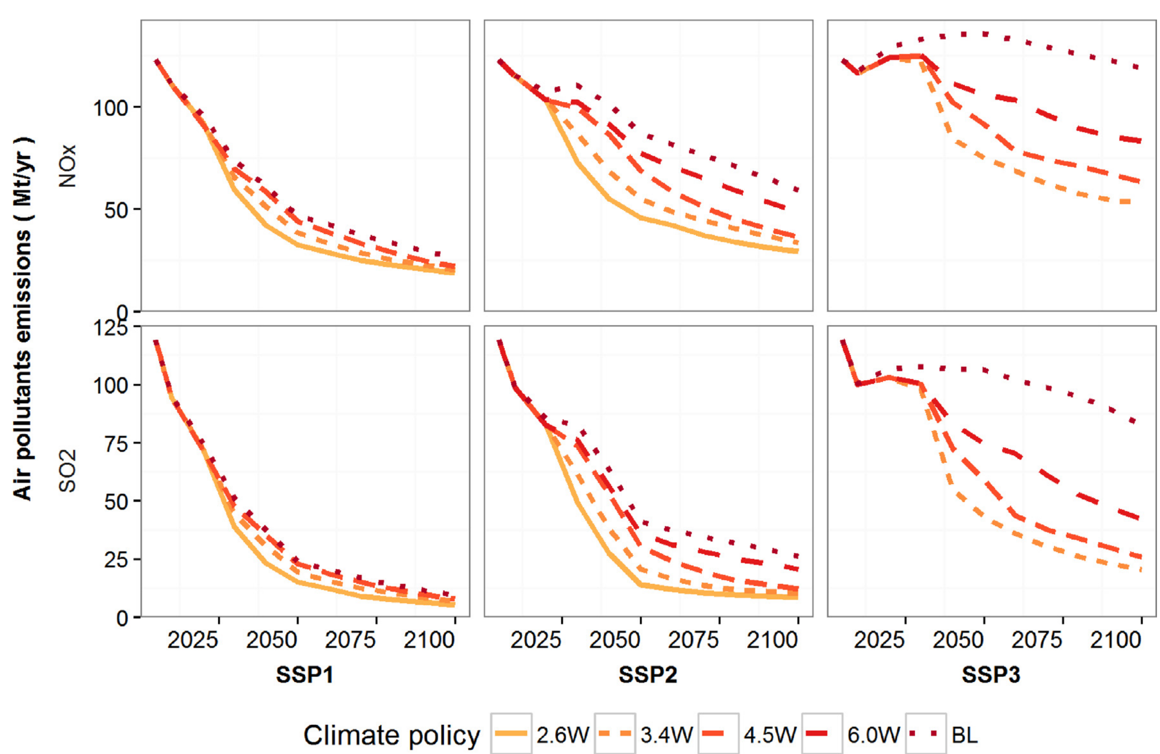

Fig. 6. Global NO_x and SO_2 (top and bottom) emissions associated with the five mitigation cases for SSP1, SSP2, and SSP3. The units in NO_x and SO_2 are $MtNO_2$/year and $MtSO_2$/year.

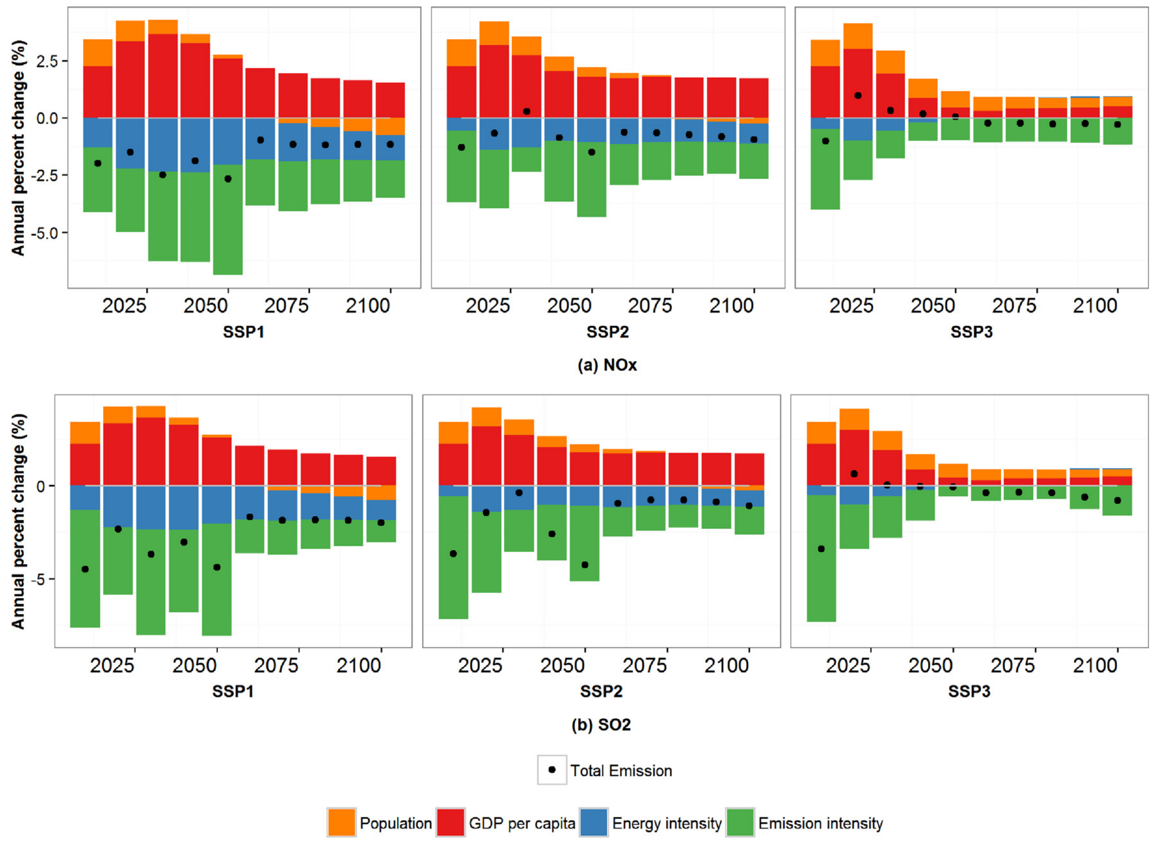

Fig. 7. Global NO_x and SO_2 (top and bottom) decomposition analysis of SSP1, SSP2, and SSP3 in baseline scenarios.

most obvious example—about 80% of SO_2 emissions in 2005 were from the energy supply and industry sectors—and they can react even at a low carbon price by changing their energy consumption structure as described above. The reductions in NO_x emissions are not as obvious as for SO_2, but they show a similar trend. Although energy supply is a major NO_x emissions source, so is the transport sector, which faces more challenges when switching fuels, and it is almost impossible to use CCS in this sector. The differences between the baseline and mitigation scenarios for other pollutants were not as large, primarily because the major emissions sources are land- use related emissions, such as forest and grassland fires, which are not easily reduced through mitigation. There is little variation between the mitigation scenarios in SSP1, probably because air pollutant emissions in the baseline case have already been reduced to nearly the maximum extent possible, and the energy system is less coal dependent, so that there is less room for emission reduction.

3.5. Radiative forcing

Radiative forcing is shown in Fig. 8(a). All baseline scenarios increase in this century, with SSP1-BL, SSP2-BL, and SSP3-BL reaching 5.4, 6.8, and 7.1 W/m^2, respectively, in 2100. The order follows the cumulative GHG emissions level for each SSP. The

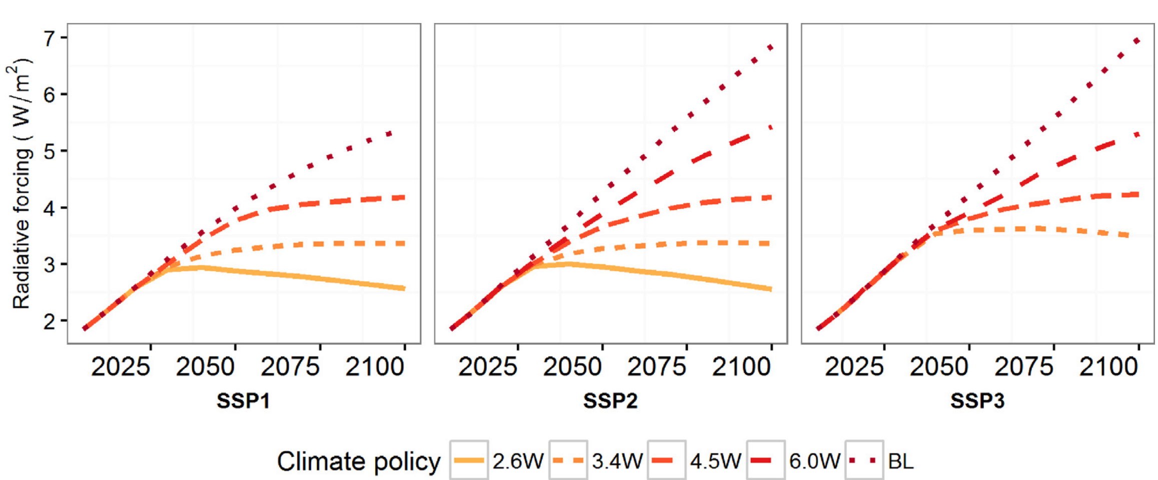

Fig. 8. Global radiative forcing associated with the five mitigation cases for SSP1, SSP2, and SSP3.

differences in radiative forcing across the SSPs in the early half of the century are not large, but increase in the latter half, whereas there are large differences in GHG emissions even in the earlier period (Fig. 5). This occurs because the climate response from long-lived GHG emissions is delayed. This climate characteristic generates another interesting outcome in SSP1-BL. Although SSP1-BL reaches near-peak GHG emissions in about 2050 and shows a decline thereafter, the amount of forcing neither stabilizes nor declines in this century. The SSP3 and SSP2-BL are similar in 2100 but the composite of the forcings are different. As we have seen in the GHG emissions, SSP3-BL has higher emissions than SSP2-BL. Thus, the radiative forcing of GHGs in SSP3-BL becomes larger than that in SSP2-BL in 2100. On the other hand, as the SO_2 in SSP3 is also higher than that in SSP2, it cancels out the GHG forcing to some degree (Supporting information SI Fig. 13). In contrast, the SSP1-2.6W and SSP2- 2.6W scenarios show overshooting of forcing temporarily during 2030–2050, after which it steadily declines in the latter part of this century (similar to RCP2.6; (van Vuuren et al., 2011b)). This trend is realized by the drastic GHG emissions reductions in this scenario (Fig. 5). The 3.4W and 4.5W mitigation cases show almost stable forcing after 2050 in all three SSPs. Such stabilization is also realized through the large GHG emissions reductions in these cases (Fig. 3). The radiative forcing figures in 2100 for the 6.0 and 4.5 W/m^2 stabilization cases are a little lower (5.4 and 4.2 W/m^2, respectively) but are consistent with the original RCPs in which forcing stabilized in 2150.

3.6. Changes in energy and carbon intensity

Global energy and carbon intensity reduction rates from 2005 to 2100 are shown in Fig. 9 (carbon intensity here considers only energy-related CO_2 emissions). Historical intensity reduction rates are extrapolated and shown as dashed lines in the figure. In terms of the baseline case, SSP2 values are most similar to historical trends. In contrast, SSP3 shows lower reduction rates in both dimensions (17% and 0%), and SSP1 shows higher rates (80% and 40%). In SSP3, the slow energy intensity improvement is derived from the assumption of slow autonomous energy efficiency improvement and high energy- service intensity. The slow carbon intensity improvement results from the assumption of a high dependence in the coal consumption and low preference for renewable energy.

The mitigation scenarios show large increases in carbon intensity improvement, while energy intensity improvements are relatively small. This implies that emissions reduction is achieved by decarbonizing the energy system. This tendency is most apparent in SSP1 but can be seen in other SSPs.

3.7. Trade dependency

Fig. 10 illustrates global trade dependencies for coal, oil, gas, rice, wheat, and coarse grains for baseline cases. The ratio of total imports to total consumption is adopted as the measure of trade dependency (total consumption is equivalent to the primary energy supply for energy goods). Overall, SSP3-BL had a lower level of trade dependency, as compared to SSP2-BL. For example, trade dependency for oil in SSP3 decreases constantly over the century, reaching 0.66 in 2100, whereas the corresponding value for SSP2-BL is 0.80. Oil, gas, and rice are goods showing a clear lower trade dependency than in SSP2. However, there are exceptions, namely wheat and coarse grains.

Two factors affect trade dependency. One is that of trade barriers implemented as trade taxes change, as indicated in Table A.1. SSP3 is assumed to have higher trade tax than SSP2 (the tax ratio in SSP3 is 33% higher than that SSP2). The other factor involves the fact that regional compositions change and the base year's level of trade dependency has an impact. For example, if a region has a high level of trade dependency in the base year and increases its trade share in the global market, the global total dependency would increase. Wheat is an example of this type of increasing trade dependency. For example, SSP3-BL has a high population increase in low-income countries, and increasing wheat consumption, despite relatively low income growth. Currently, the African region has a high share of wheat imports

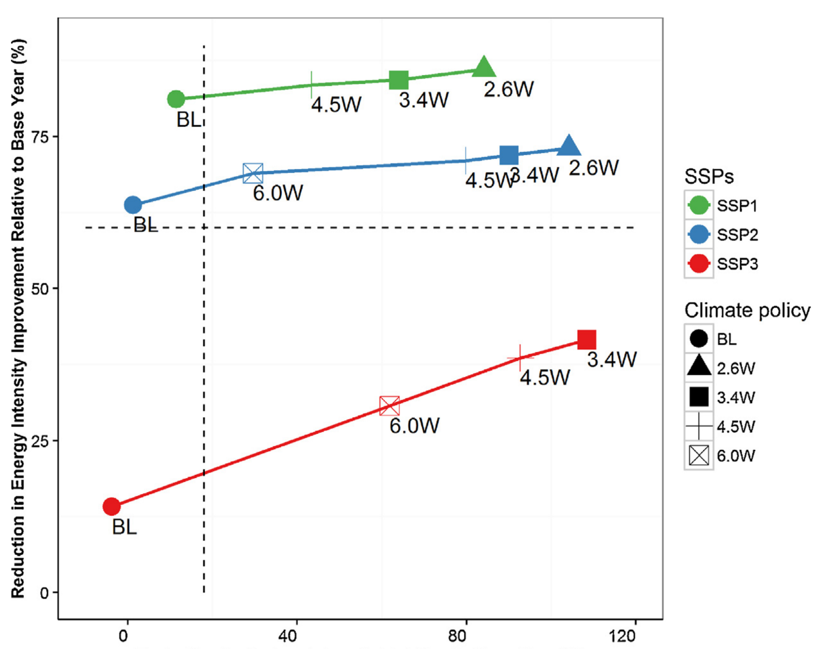

Fig. 9. global energy and carbon intensity reduction rate from 2005 to 2100. The dashed lines are extrapolation of historical rates (1970–2005). The text in the plotted area refers to the mitigation case. Carbon intensity is fossil fuel CO_2 emissions divided by total primary energy supply and energy intensity is total primary energy supply divided by GDP.

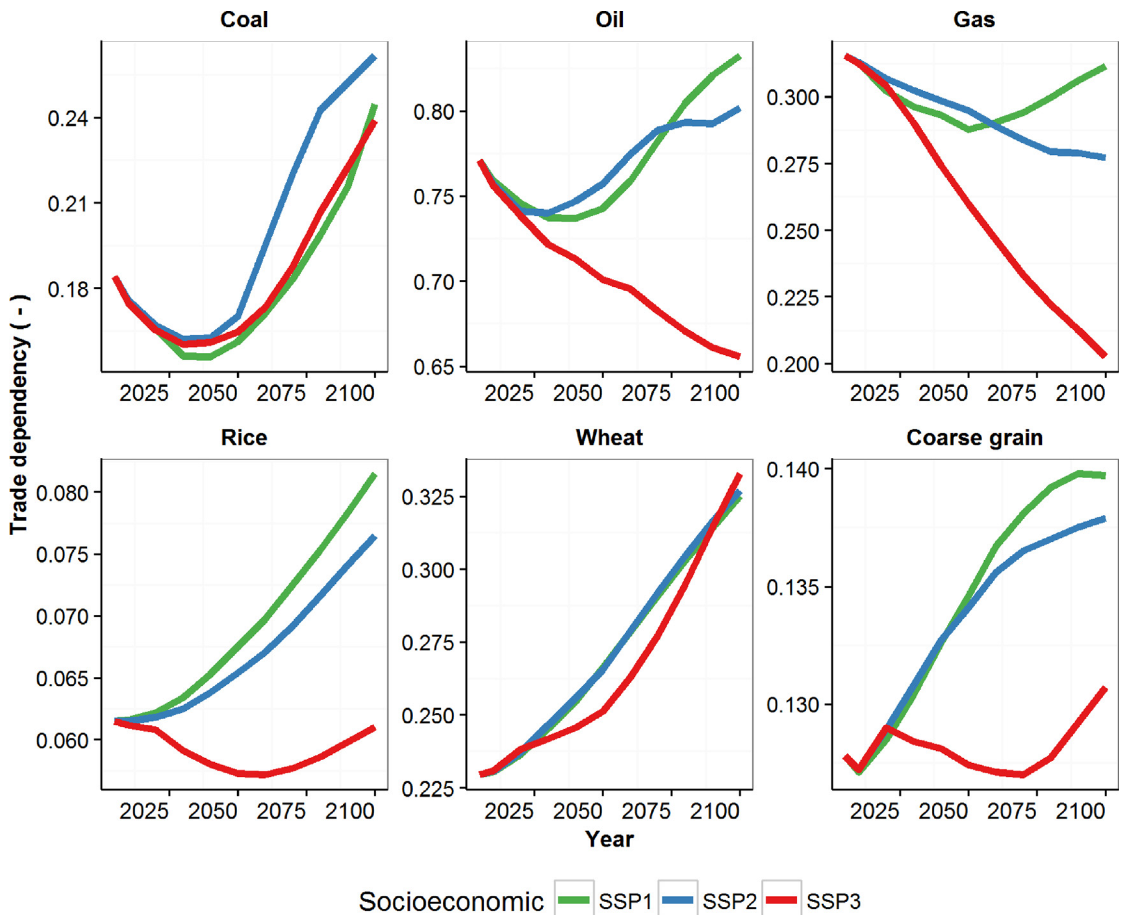

Fig. 10. Global trade dependency (oil, gas, coal, rice, wheat, and coarse grains) in SSP1, SSP2, and SSP3 baseline scenarios. Trade dependency is defined as total imports divided by total consumption.

and its share in the global market increases in the future. As a result, trade dependency in wheat increases.

3.8. Policy cost

Carbon price, GDP loss, and consumption loss are considered as measures of climate mitigation cost (Fig. 11). GDP and consumption losses are shown as percentage changes relative to values in the baseline scenarios. Carbon prices in SSP3 mitigation cases gradually increase over time. This trend can also be seen in SSP2, but the magnitude is larger in SSP3. In principle, SSP3 has greater challenges to mitigation than SSP2, and this is reflected in the carbon price. For example, the carbon price in the SSP3-3.4W scenario reaches \$1120/tCO_2eq in 2100, whereas it is \$231/tCO_2eq in SSP2-3.4W. The price is also notably higher in the SSP3-4.5W scenario, as compared to other SSPs, but the differences are negligible in the 6.0W scenarios, as compared to the more stringent mitigation scenarios. The carbon price is significantly lower in all SSP1 scenarios compared with the other two SSPs.

SSP3 has the highest annual GDP losses rate across all three climate mitigation scenarios in 2100, at 8.8%, 6.7%, and 3.2% for the SSP3-3.4W, -4.5W, and -6.0W scenarios, respectively. The corresponding GDP losses are much lower in SSP2 (1.4%, 1.0%, and 0.2%) and even lower in SSP1 (0.5%, 0.3%, and zero). In addition, both SSP2 and SPP1 were able to meet the 2.6W mitigation target, whereas SSP3 was not.

Consumption losses show very similar trends for the respective SSPs, but at a somewhat higher rate than GDP losses. This occurs because we assume that the total amount of investment is not affected by mitigation policy and is maintained at the same level as in the baseline scenario. Total global GDP consists of consumption plus investment (the trade effect is not considered); hence, only consumption loss is affected by mitigation.

Compared with the range of scenarios assessed in IPCC AR5 (Clarke et al., 2014), GDP and consumption loss of SSP2 in 2100 is slightly below (see Supporting information 5). In 2050, however, it is about the same as in IPCC AR5. This could be due to SPA assumptions about implementation, in which a fragmented climate policy is assumed in the near and medium term, and more stringent emissions reductions are required in the long term. In terms of GDP losses, SSP2 outcomes in this study are similar to, or slightly lower than, those found in the IPCC range. In contrast, GDP and consumption losses in all SSP3 mitigation cases are notably higher than those found in IPCC AR5.

4. Discussion

4.1. Evaluation of consistency with the narrative

As indicated in Section 2.5, there are three main points that must be evaluated in the context of consistency with the narrative that characterizes the SSP3 scenario: (1) the high level of mitigation challenges, (2) regional rivalry, and (3) slow technological development. With respect to the first point, there are two factors; specifically, factors that increase the baseline scenario emissions, and those that reduce mitigative capacity. The demographic and economic assumptions are exogenous in AIM/CGE, so factors such as energy efficiency improvement rate and fuel

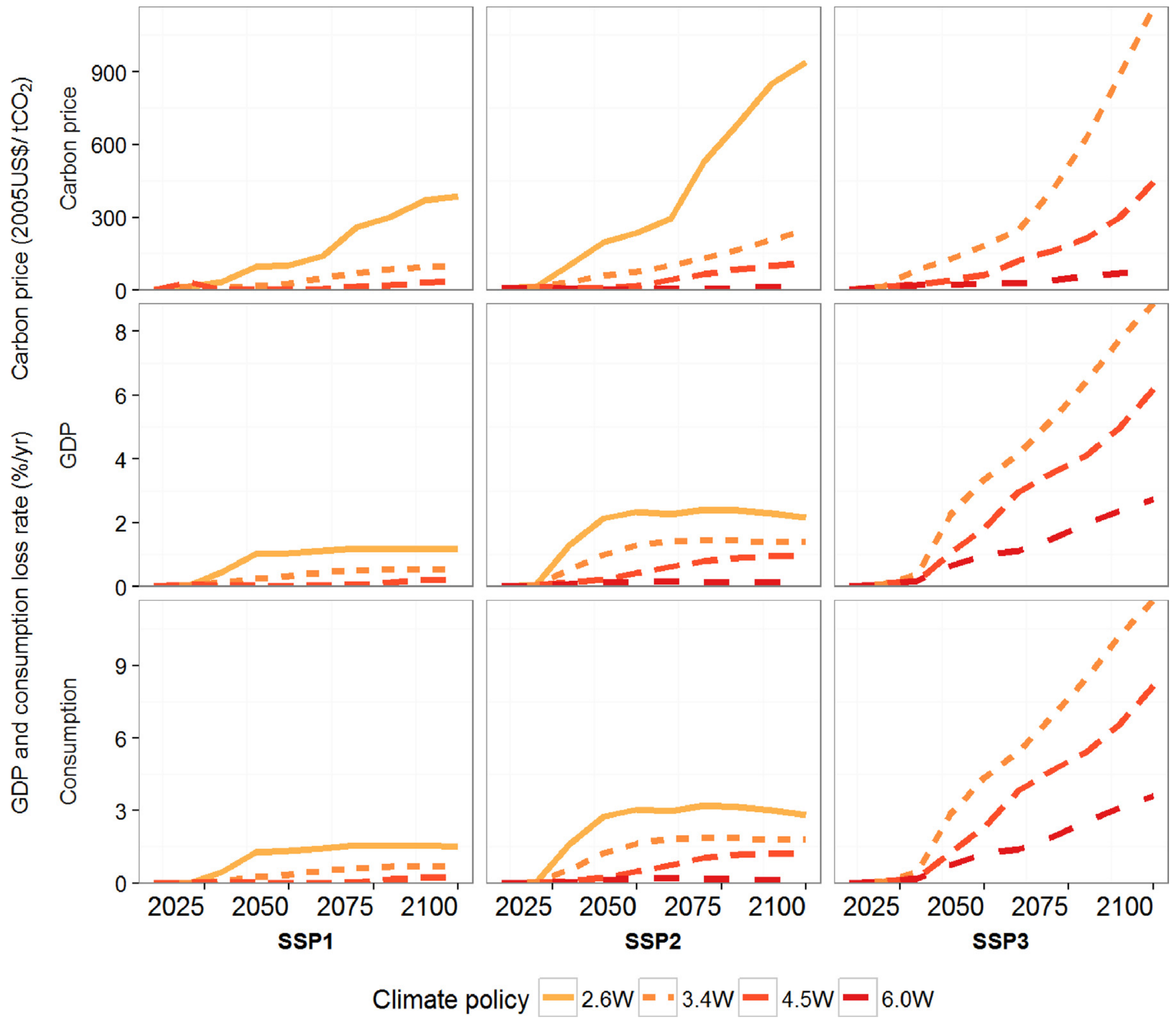

Fig. 11. Mitigation costs (carbon price, GDP loss, and consumption loss) associated with four mitigation cases for SSP1, SSP2, and SSP3. The macroeconomic losses are measured as the percentage change from the baseline scenarios.

preferences or technological developments in non-fossil fuels are relevant to this discussion point. As shown in Table A.1, these factors are specified in the SSP. The SSP3 baseline case for GHG emissions appears to be higher than SSP2 as a result of underlying assumptions (Fig. 5). We also included assumptions relevant to mitigative capacity such as CCS availability, non-CO_2 emission reduction potential, and land-use regulation. This feature makes SSP3-3.4W need large negative CO_2 emissions at the end of this century. Policy cost measures, specifically carbon price, GDP losses, and consumption losses, were all higher in SSP3 than in the other SSPs. Furthermore, SSP3 was unable to obtain results for the 2.6W stabilization case. All of these results indicate that SSP3 reflects a high level of challenges to mitigation, and we can confirm that the narrative is well represented from this perspective.

For the second point, we confirmed that the energy and agricultural trade market volumes to total production are relatively small compared with the other SSPs, which is consistent with a higher level of regional rivalry. Fragmented climate policy implementation (SPA3) is also a feature reflecting a regionally segmented world.

Finally, with regard to the third point, SSP3 has the lowest rates of energy and carbon intensity improvement, with annual mean improvement rates of 0.2% and −0.39% respectively (Section 3.6). Compared to historical trends, these rates were relatively low. Yield growth rate is also a measure used to determine the development of agricultural technologies, and SSP3 is the lowest of all the SSPs in this parameter. Taken as a whole, all three main points are consistent with the SSP3 narrative.

4.2. Limitations and uncertainties

The methods and rationales underlying the assumed parameter values listed in Table A.1 may generate uncertainty in the results. Furthermore, even if the directions of the scenario elements shown in Table A.1 are agreed upon, other studies may consider different parameter assumptions more suitable for particular SSPs. In that sense, the SSPs quantified in this paper are not unique. For example, the results in carbon price for SSP3-3.4W estimated by the four models range from 297 to 3416\$/tCO_2 in 2100. In order to identify the main uncertainty sources, we need to test the scenarios like turning on and off for the assumptions shown in Table A.1 one by one. This type of analysis is beyond the scope of this study, and may be one of the further research topics. Moreover, generally speaking, these kinds of quantitative scenarios will never generate a unique solution. Thus, we clearly stated the methodology adopted for quantification so that it may be traced by other studies. Moreover, we believe that the methodology adopted is acceptable for most scenario users.

The distinction between SPAs and SSPs remains somewhat controversial. O'Neill et al. (2014) originally suggested that SSPs should clearly distinguish socioeconomic (SSPs) and policy dimensions. Following those suggestions, SPAs were independently developed through these SSP quantification processes, and the methods of implementation of SPAs have been shared between modeling teams. However, in this paper, only combinations with corresponding socioeconomic and climate policies, such as SSP1-SPA1, SSP2-SPA2, and SSP3-SPA3, have been presented. In principle, socioeconomic scenarios include both non-climate-related and climate-related policies, meaning that a combination such as SSP1- SPA3 is theoretically possible. This type of combination was excluded in this paper, however, because of the implausibility of the combination. SSP1 is designed for a cooperative world, whereas SPA3 assumes a fragmented world in terms of climate policy. We therefore adopted the strategy of allocating only one SPA to its corresponding SSP. However, different combinations are possible (e.g., SSP1 and SPA2) and those scenarios should be investigated in future studies.

For the SSP3-2.6W scenario, we could not get a feasible solution. There are four points we can highlight regarding this issue. First, SSP3 basically has high GHG emissions from the land use sector associated with the high population and it reduces bio-energy combined with CCS and afforestation potential which would be key countermeasures to achieve a stringent climate target. Second, SPA0 and SPA1 policy cases are feasible in 2.6W, but SPA3 policy case makes it infeasible. This implies that climate policy assumption is one of the key elements to realize 2.6W stabilization in SSP3. Third, most of the IAMs (for example, IMAGE and MESSAGE) involved in the SSPs quantification process could not get a feasible solution for this scenario. It could be interpreted either that all these models lack sufficient technological representations or that SSP3-2.6W is really difficult to achieve. Fourth, although marker scenario could not show the feasible solution in SSP3-2.6W, it does not mean that SSP3-2.6W would never be realized by other IAMs.

In the evaluation process, we tested a limited number of indicators, but there may be more meaningful indicators that still need to be evaluated. For example, in addition to macro-level aggregated indicators such as total energy, energy supply and demand by individual source trends or sectoral emissions might be useful for a more complete evaluation of outcomes. However, length limitations prevent discussion of all the information generated by IAMs here. As stated, the scope of this study was to conduct a macro-overview of the SSPs. More detailed investigation should be a subject of future studies. Hasegawa et al. (2015b) provide a good example of limiting sectoral coverage (agriculture) and drawing meaningful insights from a more specific scenario quantification. This type of study could also be used to test consistency with the narrative.

4.3. Recommendations for use

SSP3 has several remarkable characteristics that are directly linked to its potential uses: (1) high level of challenges to mitigation and adaptation, (2) a similar radiative forcing level in the baseline case in 2100 as SSP2, which is generally considered to be a central baseline scenario, (3) a high level of air pollutant emissions, and (4) a relatively high deforestation rate and large expansion of cropland and pasture land. SSP3 was designed to encompass significant challenges to both mitigation and adaptation. The high cost of mitigation was confirmed. From this point of view, SSP3 has a role in presenting a scenario that society must either avoid or be prepared for, similar to the use of RCP8.5 in IPCC AR5 (IPCC, 2014). There are several aspects showing that SSP3 faces high challenges in adaptation. One is per capita income which is lower than other SSPs. Although GDP and population are inputs for the IAMs, it should be noted that low per capita income, particularly in developing countries indicates that they have less capacity to adapt to the climate change. For example, as shown in Hasegawa et al. (2015b), SSP3 has a large population increase with slow income growth and this is one of the factors behind increasing number of people at risk of hunger. A similar example is provided by Hanasaki et al. (2013b) who assess the number of population under water stress. Another aspect indicating high adaptation challenges is a large cropland expansion and deforestation. It implies that if the climate change decreases crop yield, further expansion of cropland would be restricted by limited availability of land for agriculture. Large scale deforestation would affect the ecosystem and biodiversity, and reduce their adaptation capability. In addition, stronger barriers to trade in SSP3 offer less flexibility to adapt to sudden changes in food and energy supply. In this sense, SSP3 is useful in both IAM and IAV analysis. Nevertheless, researchers must ensure that they do not overstate the problem by only showing this worst-case scenario, because providing biased information could be more harmful than beneficial in policy making.

The similarity of the SSP2 and SSP3 baseline scenarios in radiative forcing would provide a meaningful opportunity for the study of IAVs under similar climate but different socioeconomic conditions. Whereas SSP2 is characterized as having medium challenges in both mitigation and adaptation, SSP3 has a high level of challenges in both measures. The use of both scenarios may prove helpful in distinguishing differences in cost or difficulty of adaptation, and any residual damage. This type of analysis could also reveal which socioeconomic factors are more important, relatively speaking. Although IAV-relevant measures are not clearly observable in this paper, several trials have shown that SSP3 would be the most severe scenario in impact assessment studies, and that socioeconomic factors are affected much more than climate factors (Hanasaki et al., 2013a,b; Hasegawa et al., 2014; Ishida et al., 2014). They imply that even though the radiative forcing in SSP3 does not reach $8.5W/m^2$ like RCP8.5, the climate change effect is accelerated by the SSP3 socioeconomic development such as high population growth and slow technology development.

While all RCPs have a strong reduction in air pollutant emissions throughout this century, inclusion of a high level of air pollutant emissions is one of the most important features of the SSPs in terms of climate modeling. This RCP characteristic has constrained climate model simulations, particularly in studies of atmospheric chemistry. Therefore, the SSP3 baseline scenario might prove useful in these types of studies. Studies could also be conducted on the health impacts associated with air pollutants, which may be relevant when addressing developing countries' social concerns in the broader context of sustainable development. However, it should be noted that if mitigation is taken into account, even SSP3 showed a strong reduction in air pollutant emissions (Fig. 6).

The high deforestation rate and large expansions in cropland and pasture land in SSP3 may mean that a high degree of environmental degradation could be included in the broader context of sustainable development (O'Neill et al., 2017). This characteristic might be useful in land use-related studies, such as those on ecosystems, land degradation, and the carbon cycle.

These are just a few examples of the potential uses of SSP3, and this list is not intended to be exhaustive. The broader use of SSP3 together with the other SSPs is encouraged and would contribute to reinforcing the value of SSPs in general.

5. Conclusion

This paper presents quantified SSPs using the AIM/CGE model. Scenario matrix architecture was adopted for the quantification process, and applied to five socioeconomic scenarios (SSP1–SSP5) associated with five climate mitigation cases. Because AIM's SSP3 was selected as the marker scenario, the results obtained using SSP3 results were adopted as a central focus, and compared to SSP2 (the "middle of the road" scenario) and SSP1 (the opposite scenario to SSP3). We explored the main indicators of the SSPs and confirmed that the relative position of SSP3 to SSP2 (and SSP1) is consistent with their narratives. SSP3 was designed with a high level of challenges to mitigation, which is reflected in a baseline scenario with a higher level of GHG emissions than SSP2. Furthermore, high mitigation costs were observed in SSP3, namely carbon price, GDP loss, and consumption loss. Technological development is slower in SSP3 than in the other SSPs. Slow energy and carbon intensity improvement rates and a lower yield growth rate reflected this aspect of SSP3. Moreover, as discussed in Section 0, SSP3 has multiple unique characteristics within the set of SSPs that should prove useful in future studies. SSP3 may be applied in both IAM and IAV analyses to present a worst-case scenario. In addition, by comparing the results of SSP2 and SSP3 projections, IAV analysis can be used to clarify the influences of socioeconomic elements under similar climate conditions. The high level of air pollutant emissions in the SSP3 baseline scenario should be of interest in climate modeling, particularly for simulations of atmospheric chemistry.

Currently, researchers using IAMs, such as that used in the SSP quantification process, need to have more interaction with different research communities, particularly the CM and IAV communities. In addition to providing sets of scenarios, various other challenges could be addressed with greater interaction, and such communication could potentially open new discipline spaces. A land, energy and water nexus is an obvious example. Another goal is to create SSPs with high regional resolution, because an important role of SSPs is to facilitate communication between scientific researchers and policy makers. In this sense, SSPs need to be more accurate and to present regional results. Regionally aggregated results, particularly those with improved near-term estimates, are needed if researchers want to communicate their results to policy makers effectively. This study constitutes a starting point towards reaching those goals.

Acknowledgements

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Appendix A.

List of assumptions

See Table A.1.

Table A.1
List of assumptions and methods of adjusting parameters.

Element	SSP1	SSP2	SSP3	SSP4	SSP5	Corresponding parameters and adjustments
Total and labor population	Based on (Kc and Lutz, 2017)					Population and labor force.
Income growth	Based on Dellink et al. (2017)					The total factor productivity is adjusted to hit the targeted GDP.
Renewable energy cost decrease speed	High	Med	Low	High	Low	Intermediate input and factor productivity parameters of renewable energy sectors are decreased. The rate of change is calculated based on the base-year price and the 2050 power generation cost target. The 2050 target is dependent on IEA (2012) and Med is this reference value. High and low are calculated as 1.25 and 0.75 times this value, respectively.
Social acceptance of modern biomass use	Low	Med	High	High	Med	Two parameters are changed: (1) the biomass power generation logit scale parameter and (2) the transport biofuel logit share parameter. Med is the default number, which is equal across renewable energy sources. High and low are calculated as 1.25 and 0.75 times these values, respectively.
Renewable energy preference	High	Med	Med	High	Low	The renewable power generation logit scale parameter is changed. Med is the default number. High and low are calculated as 1.25 and 0.75 times this value, respectively.
Nuclear technological progress speed	Med	Med	Low	High	Med	The intermediate input and factor productivity parameters of the nuclear power sector are changed. The rate of change is calculated based on the base-year price and the 2050 power generation cost target. The 2050 target is dependent on IEA (2012), and Med is the reference value. High and low are calculated as plus or minus a 2% annual change in production costs, respectively.
Social acceptance of nuclear energy	Low	Med	High	Med	Med	The nuclear power generation logit scale parameter is changed. Med is the default number. High and low are calculated as 2.0 and 0.1 times this value, respectively.
Preference for fossil fuel-fired power plants	Low	Med	High	Med	High	The fossil fuel-fired power generation logit scale parameter is changed. Med is the default number. High and low are calculated as 2.0 and 0.5 times this value, respectively.
Autonomous energy efficiency improvement (AEEI)	High	Med	Low	High/ Low	Med	A mark-up parameter for energy input in the CES and LES functions is changed for the industrial sector and the household sector, respectively. High and low are calculated as plus or minus a 1% annual change in the AEEI percentage, respectively. The LES parameters are changed according to income elasticity. High and low are calculated as 1.25 and 0.75 times the default value, respectively. SSP4 differentiates regionally varied AEEI assumptions. SSP4 high-income countries assume the speed of SSP1 while low-income countries assume the speed of SSP3. SSP5 follows the assumption of SSP2, but the energy efficiency improvement of the transport sector is 0.5% higher.
Energy use coal preference	Low	Med	High	Low	High	The logit scale parameter in energy source selection for energy end-use sectors is changed. The coal scale parameter is changed over time. Med is the default number. High and low are calculated as plus or minus an annual 1.5% of the default number, respectively.
Energy use electricity preference or electrification speed	High	Med	Med	High	Med	The logit scale parameter in energy source selection for energy end-use sectors is changed. The electricity scale parameter is changed over time. Med is the default number. High is calculated as plus an annual 1.5% of the default number.
Speed of moving away from traditional biomass use	High	Med	Low	Low	High	A coefficient to determine traditional biomass usage is changed. Med is the default number (2% per year). High and low are calculated as plus or minus an annual 0.5% of the default number, respectively.
Service demand for transport	Low	Med	Med	Low	Med	The parameters representing household private car income elasticity and the industrial transport service coefficient are changed. For the former, med = 1.0 and low = 0.75. For the latter, med and low are set at a 0.5% and 1.0% annual improvement, respectively.
Coal mining cost	Med	Med	Low	Med	Low	

Table A.1 (*Continued*)

Element	SSP1	SSP2	SSP3	SSP4	SSP5	Corresponding parameters and adjustments
						The markup parameter for the coal mining sector production cost is changed. Med is set following Rogner (1997), but the maximum annual increase rate is assumed to 5%. Low means a 1% annual increase.
Oil and gas extraction cost	Med	Med	High	Med	Med	The markup parameters for the oil and gas extraction sectors production cost are changed. Med is set following Rogner (1997) and High has a 1.5 fold- cost. Moreover, the maximum annual increase rate is assumed to be 5%. High means a 7.5% annual increase.
Intermediate input of material decrease rate	High	Med	Low	High	Low	Intermediate inputs of steel and non-metal and mineral (cement) goods in all production sectors are changed. Med means a 2% annual decrease. High is a 3% decrease and low is a 1% decrease.
CCS (Carbon Capture and Storage) cost	Med	Med	Med	Low	Low	Productivity parameters in the CCS service provision sector are changed. Productivity parameters are intermediate inputs and primary factor input coefficients. Med is the default number (Fujimori et al., 2015) and low is calculated as 0.5 times the default number.
Social acceptance of CCS	Low	Med	Med	High	Med	The maximum CCS installation rate is changed. Med is the default value (85%). High and low are 100% and 50%, respectively.
Household preference for manufacturing goods	Low	Med	High	Low	High	Income elasticity of industrial goods is changed and is reflected in the household consumption LES parameter. Med is the default number. High and low are calculated as 1.5 and 0.75 times the default number, respectively.
Air pollution control level	Strong	Med	Weak	Weak	Strong	Legislation determines air pollutant emissions control. The details are explained in (Rao, 2017; Riahi et al., 2015) Strong indicates that the emissions coefficient of air pollutants decreases very quickly and weak means the opposite. he emissions intensity (emission per unit of primary energy) for all gases, three SSPs and climate mitigation cases is shown in Supporting information SI Fig. 10.
Non-energy-related emissions reduction measures cost	Low	Med	High	Low	High	The non-energy-related emissions reduction parameter is changed. Med is the default value (Fujimori et al., 2015). High and low are plus or minus 25% of the default value, respectively.
Yield growth assumptions	High	Med	Low	High /Low	High	The coefficient that represents land productivity is changed following Hasegawa et al. (2015b). SSP4 differentiates between high- and low-income countries, which have high and low yield growth, respectively.
Export tax and import tariff rate for agricultural goods	Low	Low	High	High	Low	The export tax and import tariff rate for agricultural goods are changed. High assumes an additional 33% of base-year amount, and low assumes no change to base-year level.
Export tax and import tariff rate for energy goods	Low	Low	High	Low	Low	The export tax and import tariff rate for energy goods are changed. High assumes an additional 33% of base-year amount, and low assumes no change to base-year level.
Livestock-oriented food consumption preference	Low	Med	High	High	Low	The income elasticity of livestock goods is changed and is reflected in the household consumption LES parameter. The actual numbers are shown in Hasegawa et al. (2015b).

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.06.009.

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