Impacts of socio-economic and climate changes on water, food, bioenergy, land use, and ecosystems

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Abstract

Future socio-economic and climate changes can profoundly impact water resources, food production, bioenergy generation, and land use, leading to a broad range of societal problems. In this study, we performed future projections by using a land integrated model, MIROC-INTEG-LAND, that considers land surface physics, ecosystems, water management, crop growth, and land use, under various socio-economic scenarios (Shared Socio-economic Pathways, SSPs). Under the sustainability scenario (SSP1), demands for food and bioenergy are kept low, so that the increase in cropland areas for food and bioenergy are suppressed. On the contrary, in the middle of the road and regional rivalry scenarios (SSP2 and SSP3), cropland areas are projected to increase due to high demand for food and bioenergy. The expansion of cropland areas is projected to increase the water demand for irrigation and CO_2 emissions due to land use change. MIROC-INTEG-LAND simulations indicate that the impacts of the CO_2 fertilization effect and climate change on crop yields are comparable, with the latter being greater than the former under climate scenarios with high greenhouse gas concentrations. We also show that the CO_2 fertilization effects and climate change play important roles in changes in food cropland area, water demand for irrigation, and CO_2 emissions due to land use change. Our results underscore the importance of considering Earth-human system interactions when developing future socio-economic scenarios and studying climate change impacts.

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Key Points:

- Impacts of socio-economic and climate changes on water, food, bioenergy, land use and ecosystems were analyzed using an integrated global land surface model.

- Cropland is projected to expand due to increased food demand and reduced crop yields caused by climate change, leading to an increased water demand and CO_2 emissions due to land use change.
- The CO_2 fertilization effects and climate change are projected to have considerable impacts on cropland area, water demand, and ecosystem production in future Earth-human systems.

Abstract (fewer than 250 words, now 216 words)

Future socio-economic and climate changes can profoundly impact water resources, food production, bioenergy generation, and land use, leading to a broad range of societal problems. In this study, we performed future projections by using a land integrated model, MIROC-INTEG-LAND, that considers land surface physics, ecosystems, water management, crop growth, and land use, under various socio-economic scenarios (Shared Socio-economic Pathways, SSPs). Under the sustainability scenario (SSP1), demands for food and bioenergy are kept low, so that the increase in cropland areas for food and bioenergy are suppressed. On the contrary, in the middle of the road and regional rivalry scenarios (SSP2 and SSP3), cropland areas are projected to increase due to high demand for food and bioenergy. The expansion of cropland areas is projected to increase the water demand for irrigation and CO_2 emissions due to land use change. MIROC-INTEG-LAND simulations indicate that the impacts of the CO_2 fertilization effect and climate change on crop yields are comparable, with the latter being greater than the former under climate scenarios with high greenhouse gas concentrations. We also show that the CO_2 fertilization effects and climate change play important roles in changes in food cropland area, water demand for irrigation, and CO_2 emissions due to land use change. Our results underscore the importance of considering Earth-human system interactions when developing future socio-economic scenarios and studying climate change impacts.

Plain Language Summary

Future changes in society and climate will have a marked impact on water, food, energy, and ecosystems, which can lead to a variety of problems in human society. In previous studies, these

issues have typically been investigated on a sector-by-sector basis because natural processes are typically simplified in models that deal with human processes, and human processes are simplified in models that deal with natural processes. We performed future projections using a land integrated model, MIROC-INTEG-LAND, which combines models of global land surface physics, ecosystems, water management, crop growth, and land use. Our numerical simulations showed that future changes in socio-economic conditions and climate are projected to impact crop yields, resulting in substantial changes in future cropland area. The increase in cropland area is projected to increase the water demand for irrigation and CO_2 emissions due to land use change. Our projections demonstrate the interconnections between the impacts of socioeconomic and climate change on water, food, bioenergy, land use, and ecosystems, indicating the importance of making projections with models that describe the interactions between Earth and human systems.

1 Introduction

Future changes in socio-economic factors and climate will have a major impact on human societies and natural ecosystems. It has been reported that the various climate impacts that occur in a wide range of sectors interact with each other (Arent et al. 2014, Smajgl et al. 2016, Albrecht et al. 2018, Liu et al. 2018, Simpson et al. 2019, Yokohata et al. 2019, Naidoo et al. 2021). For example, an increase in surface air temperatures and a decrease in rainfall due to climate change can decrease available water resources (Cisneros et al. 2014, Schewe et al. 2014, Rodell et al. 2018, Ferguson et al. 2018, Pokhrel et al. 2021, Satoh et al. 2021). Changes in climate and water resources can reduce crop yields and affect food supply, trade, distribution, and prices, impacting food availability (Schmidhuber and Tubiello 2007, Porter et al. 2014, Reisinger et al. 2014, Niang et al. 2014, West 2014, Challinor et al. 2017, Mbow et al. 2019, Hasegawa et al. 2021). It has also been demonstrated that the degradation of food security can cause health issues, such as undernutrition and forced migration (Kniveton et al. 2012, Hsiang et al. 2013, Adger et al. 2014, Smith et al. 2014, Mbow et al. 2019, Niles et al. 2021).

In studying issues related to the interactions between Earth and human systems, land use change caused by human activities is an important contributing factor to be considered (van Vuuren et al. 2012, Rounsevell et al. 2014, Lawrence et al. 2016, Popp et al. 2017, Jia et al.

2019, Yokohata et al. 2020). For example, meeting the increased food demand accompanying future population growth will require an increase in crop yield and/or expansion in cropland area, leading to shifts in land use (Foley et al. 2011, Weinzettel et al. 2013; Alexander et al. 2018). Likewise, mitigating climate change by using bioenergy crops instead of fossil fuels requires vast areas of land for cultivating bioenergy crops (Smith et al. 2013, Humpenöder et al. 2015, Popp et al. 2017, Alexander et al. 2018, Pete Smith et al. 2019, Muscat et al. 20209). Such expansion of cropland area for food and bioenergy production can result in biodiversity loss (Immerzeel et al. 2014, Kehoe et al. 2017, Molotoks et al. 2018, Ohashi et al. 2019, Wu et al. 2019, Zabel et al. 2019), among a range of other impacts. In addition, conversion of forest to cropland can lead to reduction in net carbon absorption by ecosystems (Brovkin et al. 2013, Lawrence et al. 2016, Friedlingstein et al. 2020, Ito and Hajima 2020, Ito et al. 2020), leading to accelerated global warming.

Studies based on integrated assessment and land use models have shown that there are large uncertainties in future projections of land use changes, and the results of projections differ markedly depending on the structure and assumptions of the models, and the interpretation of future socio-economic storylines (Popp et al. 2017, Alexander et al. 2017). Factors such as population, Gross Domestic Product (GDP), consumption trends, agricultural productivity, and land use regulation are important determinants of future land use change (Stehfest et al. 2019). Future climate change can also affect agricultural productivity, cropland land area, price, trade, and consumption (Nelson et al. 2014, Wibe et al. 2015, Meijl et al. 2018). Further, the implementation of climate mitigation measures such as bioenergy crop production to achieve the Paris goals can impact food consumption and increase the population at risk of hunger by raising food prices (Fujimori et al. 2019, Hasegawa et al. 2015, 2018, 2020, 2021).

In the above studies investigating the impact of future socio-economic and climate changes on the agriculture sector, simulation results of crop yields are used mainly without considering CO_2 fertilization effects (Nelson et al. 2014, Wibe et al. 2015, Meijl et al. 2018, Hasegawa et al. 2018, 2020, 2021), primarily because there are large uncertainties associated with the latter (Wang et al. 2012, Boote et al. 2013). On the other hand, the latest crop modeling studies show that it is difficult to make realistic projections of crop yields without considering the CO_2 fertilization effects (Muller et al. 2021), and studies using results using both 'with' and 'without' CO_2 simulations interchangeably can potentially lead to misinterpretation of future projections (Toreti et al. 2020).

In this study, we perform future projections by using MIROC-INTEG-LAND (MIROC INTEgrated LAND surface model, Yokohata et al. 2020), which couples the latest global models of land surface physics, water resources, crop growth, land use, and terrestrial ecosystems. In previous studies, these impact assessments have been conducted separately on a sectoral basis rather than by integrating natural and human components (Collins et al. 2015, Thornton et al. 2017, Muller-Hansen et al. 2017, Calvin and Bond-Lamberty 2018, Robinson et al. 2018, Alexander et al. 2018, Monier et al. 2018, Tachiiri et al. 2021). MIROC-INTEG-LAND provides a consistent, integrated modeling framework to examine these interconnections related to future impacts. Taking advantage of this feature, we analyzed the impacts of climate change and CO_2 fertilization effects on crop growth, land use, water resources, and ecosystem production. In addition, in order to investigate the sources of uncertainties in the future land use projections, we compared the simulations of food and bioenergy cropland area simulated by MIROC-INTEG-LAND and those obtained using the integrated assessment model AIM/Hub (Fujimori et al. 2017), both of which have the same food and bioenergy demands.

In the reminder of this manuscript, section 2 provides an outline of MIROC-INTEG-LAND. Section 3 explains the setting of socio-economic and climate scenarios. Section 4 shows the results of future projections estimated by MIROC-INTEG-LAND, focusing on the interactions between climate, water resources, crops, land use, and ecosystems. Section 4 also investigates the impact of climate change and CO_2 fertilization effects on crop yield, cropland area, irrigation water, and ecosystems, and discusses the reasons for the differences between MIROC-INTEG-LAND and AIM/Hub. Finally, Section 5 summarizes our findings and important future work.

2 Model Description

Figure 1 shows the overall framework of the integrated land surface model MIROC-INTEG-LAND. The model was evaluated against observations made in our previous study (Yokohata et al. 2020). Since MIROC-INTEG-LAND is based on the land surface component of a global climate model MIROC (Model for Interdisciplinary Research on Climate version: Watanabe et al., 2010), future climate scenarios are prescribed as the boundary conditions (details in Section 3.2). In terms of socio-economic scenarios, GDP, the demands induced by food (including feed) and bioenergy crop production, pasture area development, and timber extraction (Terrestrial Land-use Model, Yokohata et al. 2020) are prescribed in the land use sub-model, TeLMO. The demands for domestic and industrial water abstraction are prescribed in the water management sub-model, HiGWMAT (Pokhrel et al. 2015). In the crop growth sub-model, PRYSBI2 (Sakurai et al. 2014), future technological developments factors that increase crop yields are described as a function of GDP. For the data related to these socio-economic scenarios, the results estimated by the integrated assessment model AIM/Hub (formerly AIM/CGE) (Fujimori, Hasegawa et al. 2017) are used.

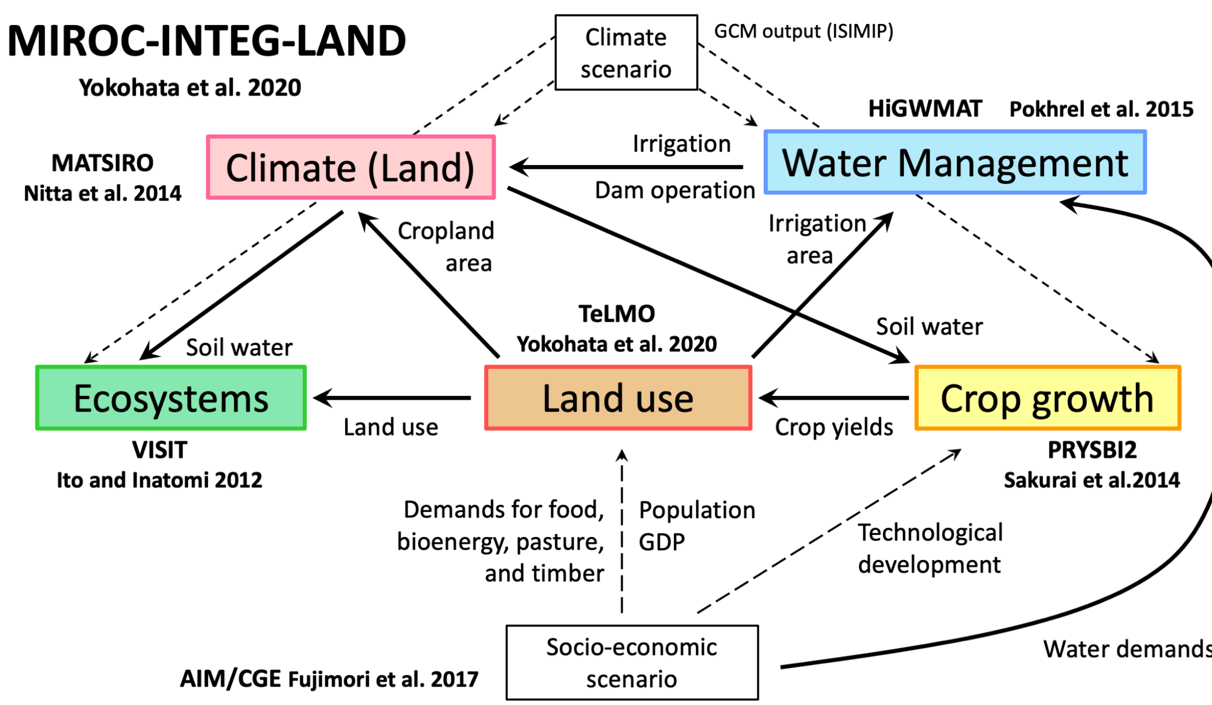

Figure 1. Structure of the global land integrated model MIROC INTEGrated LAND (MIROC-INTEG-LAND, Yokohata et al. 2020). Colored boxes represent sub-models, and arrows indicate

variables that are exchanged. The names of the sub-models are also indicated in bold. The boxes "Climate scenario" and "Socio-economic scenario" represent input data to the model. Modified from Figure 1 in Yokohata et al. 2020.

Agricultural water demand was simulated in the water management sub-model HiGWMAT (Pokhrel et al. 2015), withdrawn from rivers, reservoirs, and groundwater, and added to the soil during the irrigation period. River flow regulation by dams is simulated using a reservoir operation scheme in the HiGWMAT model. In irrigated grid cells, soil moisture and evaporation amount in the land surface model MATSIRO (Minimal Advanced Treatments of Surface Interaction and Runoff, Takata et al. 2003, Nitta et al. 2014) are updated using an irrigation scheme, and the calculated soil moisture and temperature are given to the crop growth model PRYSBI2 (Sakurai et al. 2014). In PRYSBI2, five types of crops (spring and winter wheat, rice, soybeans, and maize) are simulated over the global land area at a latitude/longitude resolution of 1°. Key parameters that determine crop yield, such as the total number of heat units until harvest (calculated based on degree days) and technological development factors, are determined in each grid by using a statistical method (Sakurai et al. 2014) using historical global yield data (Iizumi et al. 2014). The CO_2 fertilization effect in PRYSBI2 is formulated by using the Farquhar model (Farquhar et al. 1980), and parameters of photosynthesis are calibrated according to the observations (Sakurai et al. 2014, Yokohata et al. 2020). The decrease in crop yields due to changes in temperature and water stress is calculated using PRYSBI2.

Crop yield simulated by PRYSBI2 is utilized by the land use model TeLMO (Yokohata et al. 2020). In TeLMO, the areas of cropland for food and bioenergy production, pastureland, and natural and managed forest are calculated on a global 0.5° grid. In TeLMO, the food cropland model has a cropland down-scaling module, which estimates an agricultural suitability index based on the crop yields obtained from PRYSBI2, 30-second resolution slope data, GDP of 17 regions around the world estimated by AIM/Hub, and food crop price (solved in TeLMO). In TeLMO, the area ratio of food cropland in the grid cell is more likely to be large if the agricultural suitability index of a grid cell is large. The agricultural suitability index is formulated based on the satellite observations of cropland area (Friedl et al. 2010). The food cropland model in TeLMO also has an international trade module, which estimates prices in 17 regions around the world by solving a general equilibrium model in two sectors; the agricultural and the non-agricultural sectors (Ejiri 2008).

An important feature of TeLMO is that the detailed spatial distribution of crop yield and cropland distribution are considered when allocating the food cropland area. Specifically, crop yield and cropland area in each grid cell are used to estimate the balance of the food supply and demand over 17 global regions using the general equilibrium model. Typically, integrated assessment models use the average crop yield for each region to calculate the cropland area required for each region; consequently, it has been demonstrated that the spatial distribution of crop yields cannot be fully reflected in the estimates of cropland area (Alexander et al. 2018). This issue is addressed in TeLMO by considering the spatial distribution of crop yield and cropland area for each grid cell. In the TeLMO food cropland model, adjustment parameters are obtained and used so that the cropland area in the base year (2005) matches satellite observations (Hurtt et al. 2020).

In the TeLMO bioenergy cropland model, the agricultural suitability index is formulated in a similar manner to the food cropland model. The price of bioenergy crops is adopted from the results of AIM/Hub. For the bioenergy crop yields, we used the yields of second-generation bioenergy crops (switchgrass, miscanthus) estimated by Kato and Yamagata (2014) using the SSP scenarios in Mori et al. (2018), and selected the higher yield value of the two crops for each grid.

TeLMO considers only bioenergy crop production as a climate mitigation measure. TeLMO calculates the decrease in forest area (deforestation) by considering timber demand, but does not consider afforestation or carbon capture and storage (CCS) as climate mitigation options. The development of forest management, afforestation, and CCS schemes are thus important areas of future work for model improvement.

The terrestrial ecosystem model VISIT (Vegetation Integrative SImulator for Trace gases, Ito & Inatomi 2012, Ito et al. 2018) uses the area ratio of the food and bioenergy crops, pasture, and forest (and transition matrix between them) calculated by TeLMO. In this way, the net CO_2 emissions associated with changes in land use can be estimated from the changes in the carbon balance (Ito 2019). In the VISIT model, plant photosynthesis is a function of ambient

CO_2 concentration, solar radiation, temperature, and soil moisture. Elevated CO_2 concentrations promote the fertilization effect, but the strength of this effect varies with climatic conditions.

3 Experimental Settings

3.1 Socio-economic scenarios

In this study, combinations of multiple socio-economic and climate scenarios are used to project future changes in water resources, crops, land use, and ecosystems by MIROC-INTEG-LAND. We considered the following three socio-economic scenarios that are based on the SSP framework (O'Neil et al. 2017, Riahi et al. 2017).

SSP1: Sustainability – Taking the green road

SSP2: Middle of the road

SSP3: Regional rivalry – A rocky road

Supplementary Table S1 summarizes the characteristics of each SSP as it applies to the estimates obtained using MIROC-INTEG-LAND. The characteristics of each socio-economic scenario are explained in Section 3.3.

3.2 Climate scenarios

In this study, daily bias-corrected climate model outputs from four models provided by the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP, Hempel et al. 2013) are used to drive the land surface physical process model (MATSIRO), crop growth model (PRYSBI2), and terrestrial ecosystem model (VISIT). MATSIRO requires surface air temperature, precipitation, wind speed, specific humidity, solar radiation, and surface pressure at 3-hourly timesteps; the daily data are converted to 3-hour values based on the method proposed by Debele et al. 2007 and Willet et al. 2007. The five climate models are GFDL-ES2M (Dunne et al., 2012), HadGEM2-ES (Jones et al., 2011), IPSL-CM5A-LR (Dufresne et al., 2012), Nor-ESM (Bentsen et al., 2012), and MIROC-ESM-CHEM (Watanabe et al., 2011). For each model, four Representative Concentration Pathways (RCP2.6, 4.5, 6.0, 8.5, from 2006 to 2100) are used.

3.3 Combination of socio-economic and climate scenarios

Future projection experiments by MIROC-INTEG-LAND are conducted based on the three socio-economic scenarios (SSP1-3) and four climate scenarios (RCP2.6, 4.5, 6.0, 8.5). As explained above, MIROC-INTEG-LAND uses the results of the integrated assessment model AIM/Hub as input, but in the calculations of AIM/Hub, the scenarios SSP1-RCP6.0 and SSP1-RCP8.5, SSP2-RCP8. 5, SSP3-RCP8.5 are not available. This is because the greenhouse gas (GHG) concentrations in the AIM/Hub baseline scenario are lower than RCP6.0 for SSP1 and lower than RCP8.5 for SSP2 and SSP3. Therefore, in future projection simulations, the SSP1-baseline results estimated by AIM/Hub are used for SSP1-RCP6.0, those of the SSP2-baseline for SSP2-RCP8.5, and those of the SSP3-baseline for SSP3-RCP8.5. It should be noted that there is an unavoidable inconsistency between the input value estimated by AIM/Hub and other estimates for SSP1-RCP6.0, SSP2-RCP8.5, and SSP3-RCP8.5. This inconsistency arises because there is no bias-corrected climate scenario equivalent to the SSP1-, SSP2-, and SSP3-baselines in AIM/Hub. These inconsistencies are resolved when MIROC-INTEG-LAND is coupled with an Earth System Models (ESMs) (Yokohata et al. in preparation) by calculating these climate scenarios using the ESM component.

Figure 2 shows the time series of socio-economic scenarios, calculated by the integrated assessment model AIM/Hub. Population depends solely on SSPs (KC & Lutz 2017). In SSP1, which is a sustainability scenario, population growth is suppressed and the population decreases after 2050. Under SSP3, the population continues to grow, reaching around 13 billion by 2100. On the other hand, GDP increases significantly in SSP1 and SSP2, but not substantially in SSP3 (Dellink et al. 2017). GDP is hardly dependent on climate scenarios, partly because it does not consider the effects of climate change.

Future changes in food demand show a small increase in SSP1 and a large increase in SSP3, with SSP2 in between. Changes in food demand are not dependent on climate scenarios. On the other hand, future increases in the demand for bioenergy crops depend on both socio-economic and climate scenarios. The demand for bioenergy crops is generally low for SSP1, as in the case of food demand. In SSP2, the demand for bioenergy crops under the RCP2.6, 4.5, 6.0

scenarios is large, larger than that in SSP1. The demand for bioenergy crops under RCP4.5, 6.0 in SSP3 is even greater than that in SSP2.

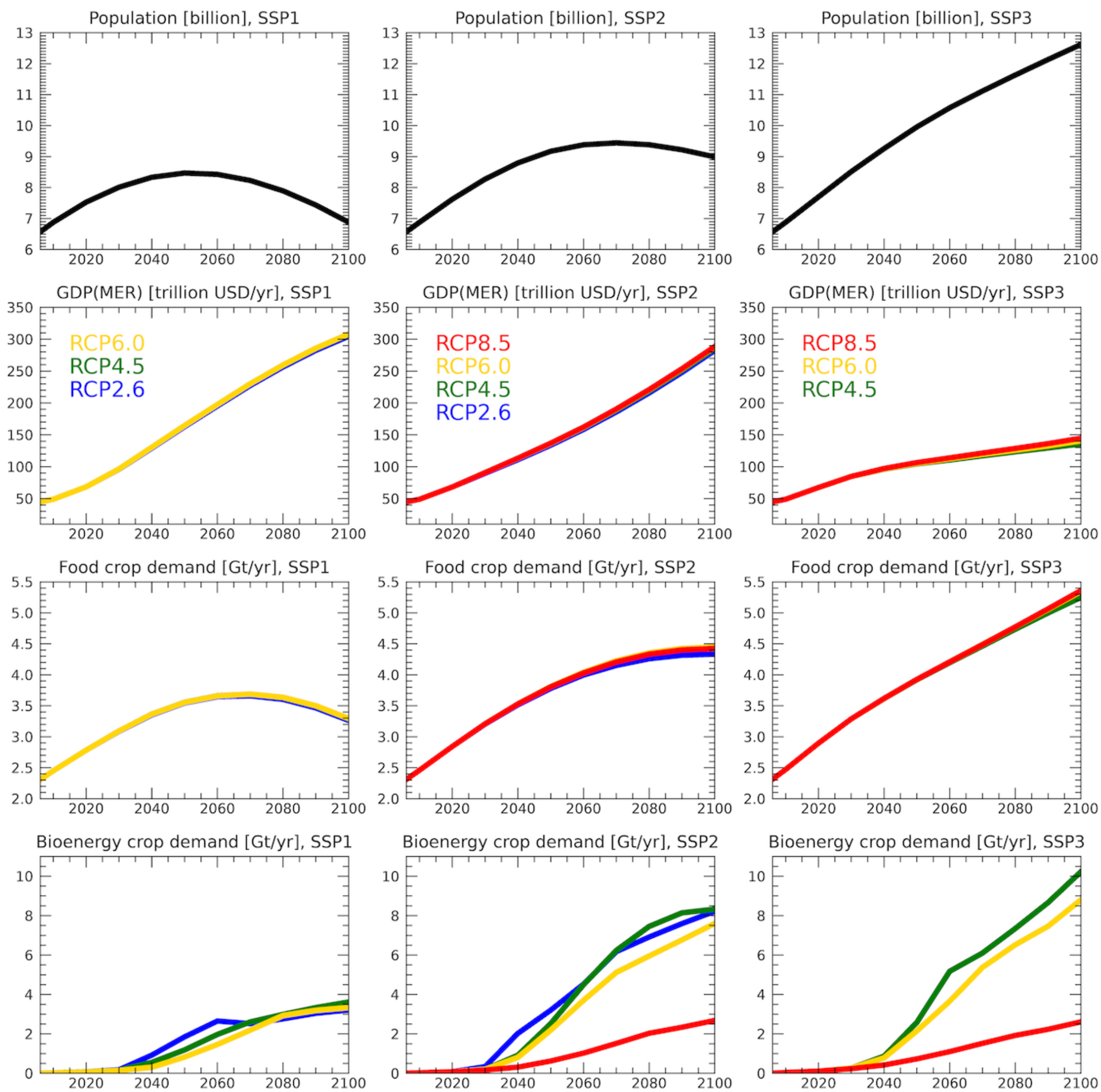

Figure 2. Time sequence of the sum of the global population (1^{st} row), GDP (2^{nd} row), food crop demand (3^{rd} row), and bioenergy crop demand (4^{th} row) under the SSP1 (left), SSP2 (middle), and SSP3 (right) scenarios used as inputs to MIROC-INTEG-LAND. Population does not

depend solely on representative concentration pathways (RCPs), so it is shown in black. The line colors show the results obtained for the RCP2.6 (blue), RCP4.5 (green), RCP6.0 (yellow), and RCP8.5 (red) scenarios. See Section 3.3 for details on SSP-RCP combinations. Time sequences are calculated using AIM/Hub.

4 Results

4.1 Changes in climate conditions

MIROC-INTEG-LAND uses atmospheric variables, such as surface air temperature and precipitation, as inputs for the model, and calculates the land surface variables, such as soil moisture/temperature, and river flows, in the model. As shown in Figure S1, the variations in surface air temperature rise and precipitation differ depending on the GHG concentration scenarios. In the RCP8.5 scenario, where the surface air temperature rises the most, precipitation increases, but average global soil moisture decreases. This is because evapotranspiration increases globally as the surface air temperature rises. In addition, the future drought months in a year are projected to increase as temperatures rise (Figure S2). Here, we defined the drought months as the months when river flows are less than 20% of historical values. Figure S2 shows that the number of drought months increases with the magnitude of climate change. In general, future climate warming is projected to promote drying of the land surface in the climate model ensemble used in this study.

4.2 Changes in crop yields

Figure 3 shows future changes in crop yields. The land-use model TeLMO uses the maximum yield of the five crops in each grid cell for the projection of cropland area (Yokohata et al. 2020). Figure 3 shows the time series for the maximum yields of the five crops in each grid cell averaged over the cropland area in the base year (2005). In the crop growth model PRYSBI2, future crop yields are generally determined by the CO_2 fertilization effects, climate change, and technological development. As shown in Figure 3, higher CO_2 concentrations in the climate scenario tend to have greater increases in crop yields; for example, the yields under

RCP6.0 and RCP4.5 are higher than those under RCP2.6. On the other hand, under RCP8.5, the crop yield is projected to decrease in the latter half of the 21st century due to the large influence of climate change and the shortening of the growing period as the temperature rises (the growing period is estimated from total number of heat unit based on degree days; Yokohata et al. 2020).

Furthermore, in PRSYBI2, the increase in crop yield due to future technological developments is formulated as a function of GDP (Sakurai et al. 2014). Therefore, differences in the SSP scenarios also contribute to the future crop yields. Compared to SSP1 and SSP2, the effect of increasing yields through technological developments is smaller under the SSP3 scenario because GDP growth is slower.

Crop yields increase globally under RCP2.6, RCP4.5 and RCP6.0 (Figure S3). Under RCP8.5, the changes are mixed with a decrease in crop yields in the mid-latitudes (i.e., North America, Europe and inland Australia) and an increase in the low-latitudes (i.e., Africa and South America). The increase in crop yields is related to CO_2 fertilization effects and technological development, while the decrease is due to the effect of climate change (i.e., shortening of the growing period; Yokohata et al. 2020). A mechanistic description of the impacts of CO_2 fertilization effects and climate change on crop yields is provided in Section 5.

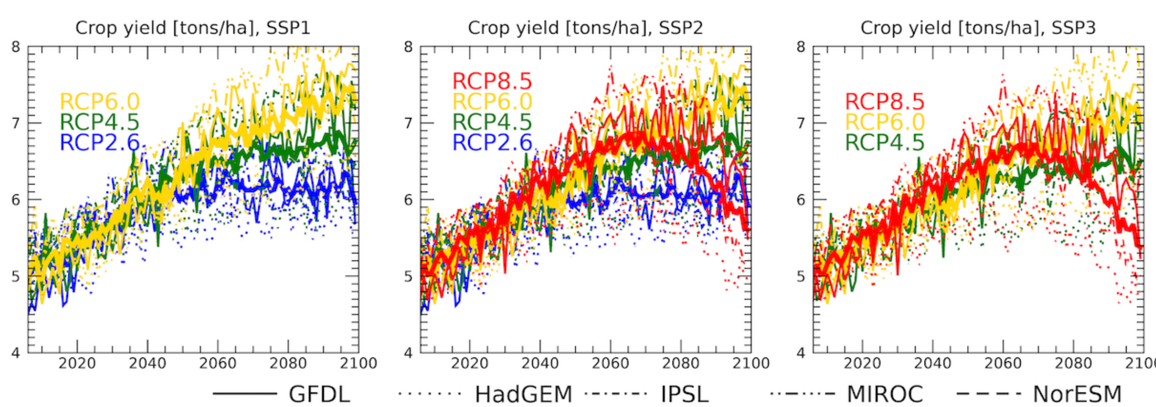

Figure 3. Time sequence of the maximum yield of five crops per grid calculated by MIROC-INTEG-LAND. The maximum yield of five crops in each grid is weighted by the cropland area in the year 2005 (unit: tons / ha). The line colors show the results obtained under the RCP2.6 (blue), RCP4.5 (green), RCP6.0 (yellow), and RCP8.5 (red) scenarios. Thin lines are the results obtained from four GCMs, and thick lines are the average values obtained from four GCMs.

4.3 Changes in food and bioenergy cropland area

Figure 4a shows the future changes in food cropland area simulated by MIROC-INTEG-LAND. For comparison with the calculation results by MIROC-INTEG-LAND, Figure 4b also shows the results of food cropland area by AIM/Hub (Fujimori et al. 2017). The MIROC-INTEG-LAND results under SSP1 show that the increase in food cropland area is small relative to other SSPs because the demand for food crop is small under the SSP1 scenario (Figure 2). As for their dependence on the climate scenario, the cropland area under RCP2.6 is relatively large compared to that under RCP4.5 or RCP6.0, because the food crop yield is suppressed due to the lower CO_2 fertilization effect. On the other hand, under RCP8.5, the food cropland area is projected to increase in the latter half of the 21st century because the crop yields are projected to decrease due to the impacts of climate change, as shown in Figure 3. With SSP3-RCP 8.5, the food cropland area in 2100 is projected to expand to about twice that of the 20th century. Details of the impacts of CO_2 fertilization effects and climate change on crop yields are discussed in Section 5.

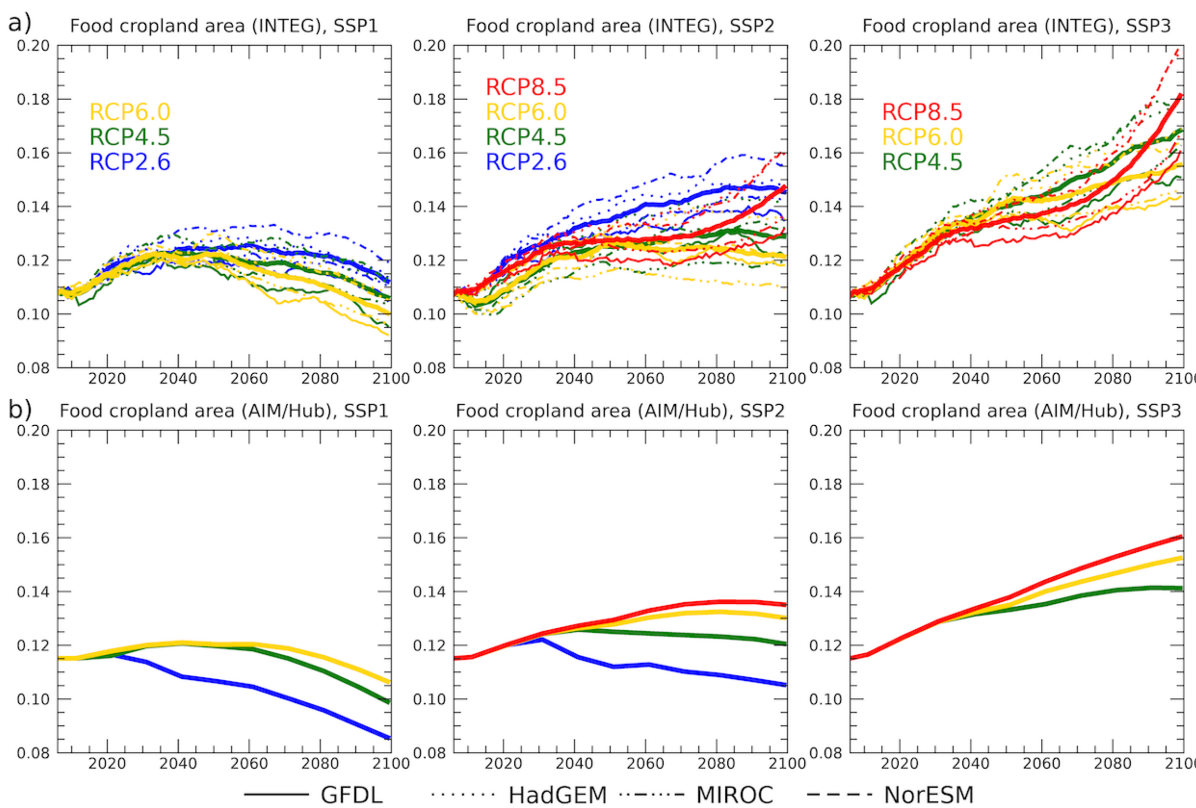

Figure 4. Time sequence of food cropland area calculated by MIROC-INTEG-LAND (top row). The results of the SSP1 (left), SSP2 (middle), and SSP3 (right) scenarios. The cropland area is calculated by AIM/Hub (bottom row). The unit is the ratio of cropland area to the global land area. Line colors and styles are the same as those in Figure 3, but the results obtained using AIM/Hub have only one ensemble member.

Figure S4 shows global maps of changes in the food cropland area estimated using MIROC-INTEG-LAND. Under all SSPs, the food cropland area tends to increase in North and South America. Changes in the food cropland area in Africa, India and China have different outcomes depending on the SSPs. Under SSP1, the food cropland area is projected to decrease in Africa, India, and China. On the other hand, under SSP2 and SSP3, the food cropland area is projected to increase in Africa, India and China, and the expansion is particularly large under SSP3. In Africa, India and China, the changes in food cropland area differs markedly depending on the population growth and food demand (Figure 2).

Figure 4b shows the time sequence of food cropland area estimated using AIM/Hub. As for the dependency on socio-economic scenarios in AIM/Hub, the cropland area is projected to decrease under SSP1, increase slightly under SSP2, and increase by up to 50% under SSP3 (Figure 4b). This dependency in the SSP scenarios should be interpreted as demand- and supply-side drivers. For the demand side, SSP1 is characterized by having a low population and low consumption in livestock-related goods, which leads to relatively low agricultural production. In contrast, SSP3 has a larger population than the other SSPs and a relatively high livestock-related demand; consequently, the cropland requirement is high. Considering the supply side, the crop yields under SSP1 are assumed to be higher than those under either SSP2 or SSP3, based on the storylines of the SSPs (O'Neill et al. 2017), which can also be a factor contributing to the decrease in cropland area in AIM/Hub.

As for the dependency of the climate scenario (RCPs) employed in AIM/Hub, the more mitigation measures are taken, the lower the expansion of food cropland area will be, as shown in Figure 4b. The climate policy factor in AIM/Hub is also associated with the supply-side stories. For example, land demand pressure would increase owing to an expansion in bioenergy demand and afforestation under low-carbon scenarios, such as RCP2.6. Consequently, land rent and crop yield could both increase due to such increases in land demand. Thus, both demand- and supply-side changes would reduce cropland area under RCP2.6 (Figure 4b).

Figure 5a shows the future changes in bioenergy cropland area simulated by MIROC-INTEG-LAND. The results of the expansion in bioenergy cropland area differ markedly depending on the socio-economic scenario. As in the case of food cropland area, the demand for bioenergy crops is small under SSP1 compared to that under SSP2 and SSP3 (Figure 2), so the expansion of bioenergy cropland is small. As for the dependence on climate scenarios, bioenergy cropland areas are needed earlier and more extensively in scenarios where aggressive mitigation measures are implemented, such as those under RCP2.6 (Figure 5a).

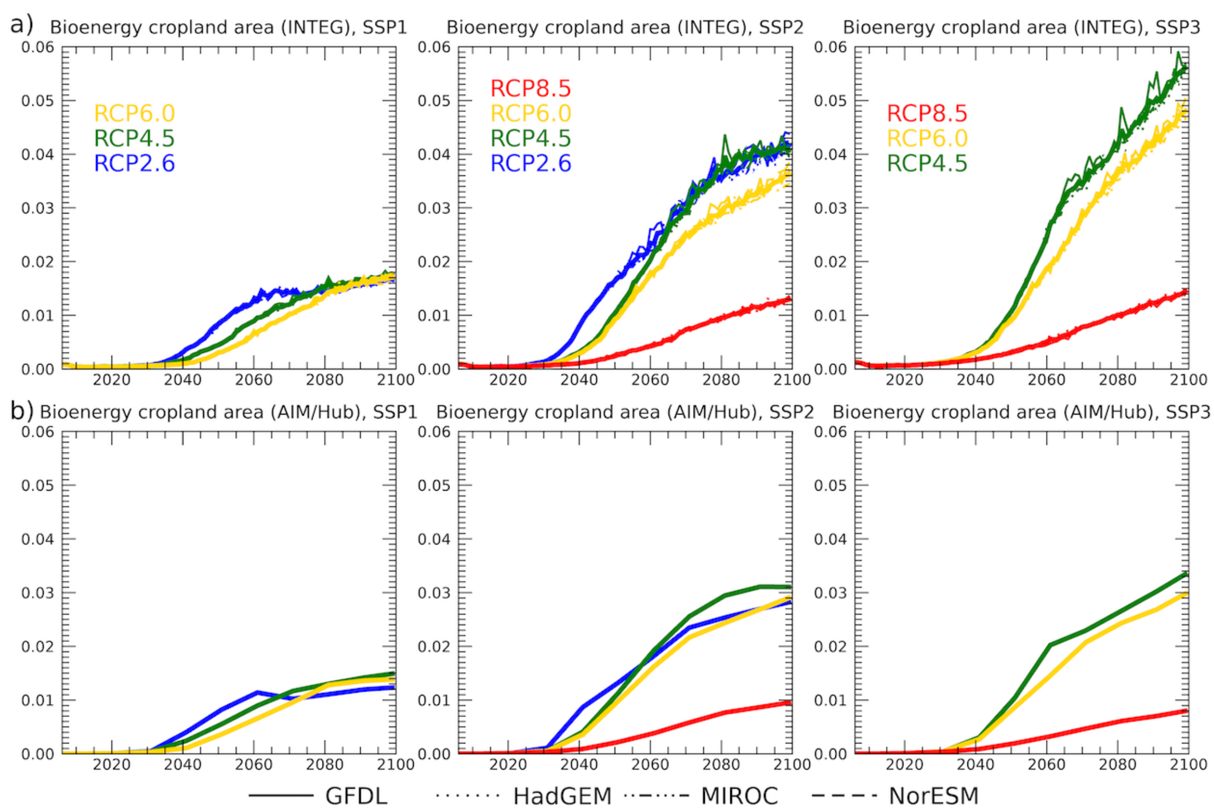

Figure 5. The same as Figure 4, but graphs show the bioenergy cropland area.

Figure S5 shows the global distribution of changes in the bioenergy cropland area in MIROC-INTEG-LAND. The bioenergy cropland area is projected to increase in Africa, Australia, South America, and North America under all scenarios. Note that TeLMO assumes that bioenergy crops are not grown in biodiversity hotspots (Yokohata et al. 2020). Changes in bioenergy cropland area are greater in these areas under SSP2 and SSP3 compared to those under SSP1, and under RCP2.6 and RCP4.5 compared to those under RCP8.5.

Figure 5b shows the results of the bioenergy cropland area estimated by AIM/Hub using the same bioenergy crop demands as MIROC-INTEG-LAND. As in the case of food cropland area, MIROC-INTEG-LAND requires a larger bioenergy cropland area compared to AIM/Hub, with the shape of the curves and the order of the scenarios being similar between the two models. The results shown in Figure 5a and 5b are consistent with those of Kato and Yamagata (2014), who showed that the supply of bioenergy crops calculated using a process-based crop model is larger than that calculated by integrated assessment models. This result is also affected by the fact that the biofuel crop model employed in Kato and Yamagata (2014) considers C_4 herbaceous plants which are relatively resistant to drying and high temperatures, and have small CO_2 fertilization effects.

In AIM/Hub, the degree of bioenergy cropland expansion is dependent on pressure for decarbonization from the energy system side. The stringency of the climate mitigation targets would determine the scale of land required for bioenergy. Regarding the variations in SSP, again the energy system-side requirements would be a critical factor, as the SSP1 scenario is relatively dependent upon variable sources of renewable energy, such as solar and wind, whereas the SSP3 scenario is dependent on biomass. Taken together, these dependencies account for the observed differences in bioenergy cropland area (Figure 5b).

Figure 6a shows the sum of food and bioenergy cropland area estimated by MIROC-INTEG-LAND. As discussed above, differences in socio-economic scenarios play a major role in the sum of food and bioenergy cropland area, with SSP1 keeping the increase in cropland area relatively small and stabilizing changes in cropland area in the middle of the 21st century. In contrast, under the SSP2 and SSP3 scenarios, cropland area is projected to keep increasing throughout the 21st century. Under the SSP2 and SSP3 scenarios, the increase in demand for bioenergy crops in RCP2.6, RCP4.5, and RCP6.0, and the decrease in food crop yield due to climate change in RCP8.5, leading to an expansion in food cropland area.

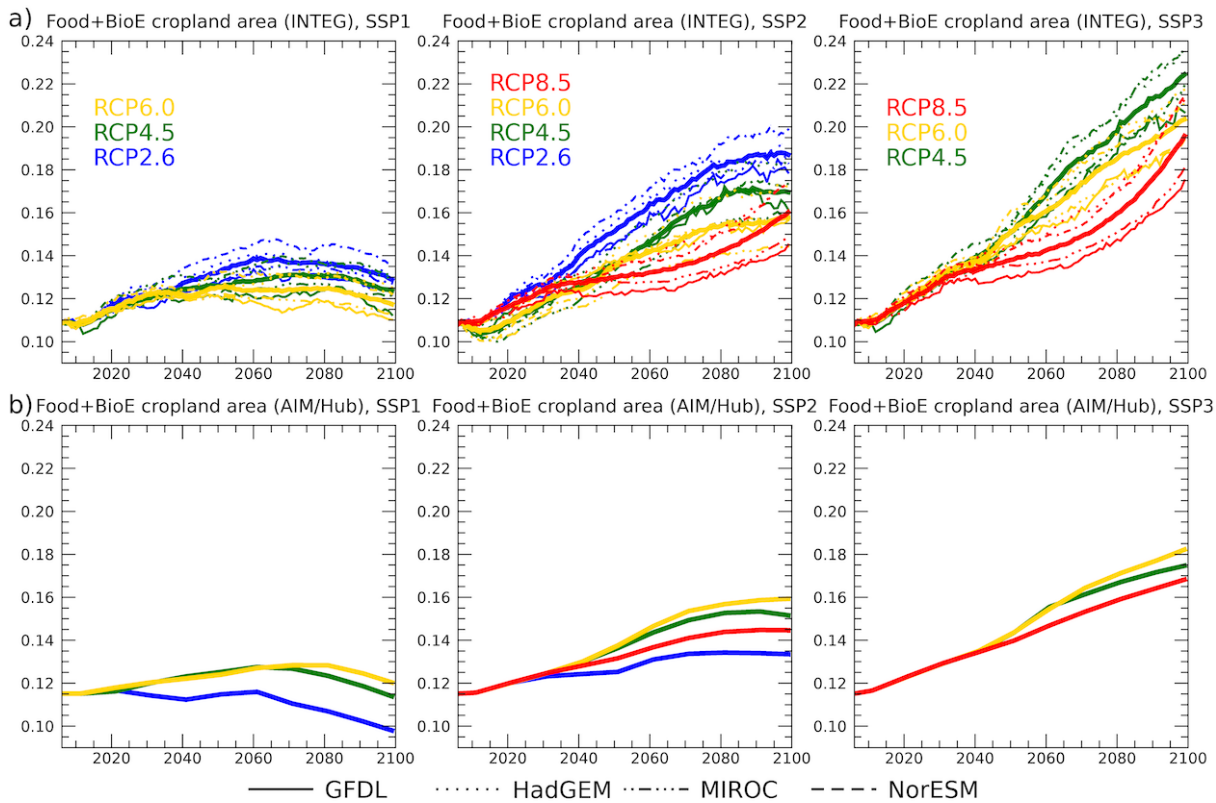

Figure 6. The same as Figure 4, but graphs show the sum of food and bioenergy cropland areas.

Figure S6 shows the spatial distribution of changes in the sum of food and bioenergy cropland areas in MIROC-INTEG-LAND. As mentioned earlier, under SSP1, the food cropland area is projected to decrease in Africa and India, and the biofuel cropland area is projected to increase slightly in Africa, Australia, South America, and North America. On the other hand, under SSP2 and SSP3, the food cropland area is projected to increase in Africa, India and China, and the bioenergy cropland area is projected to expand in Africa, Australia, South America, and North America. In South and North America, under all socio-economic and climatic scenarios, both food and bioenergy cropland area increases, and thus the increase in the sum of these cropland areas becomes large.

Figure 6b shows that the sum of food and bioenergy cropland area estimated by AIM/Hub is smaller than the increase estimated by MIROC-INTEG-LAND. One of the reasons for the disparity between the two models is that they have different food and bioenergy crop yields. The results of Figures 4 to 6 show that even if the future food and bioenergy demands are the same, the results of the cropland area are projected to differ markedly depending on the crop yield and the method used to estimate the cropland area. Details of the impacts of CO_2 fertilization effects and climate change on food cropland area, as well as the differences in the future projections of food cropland area between MIROC-INTEG-LAND and AIM/Hub are discussed in Section 5.

4.4 Changes in water demand and ecosystems

One consequence of the expansion of food cropland area is that there will be an increase in water demand for irrigation. Figure 7a shows the irrigation water demand (the amount of water abstracted from rivers and groundwater for irrigation) estimated by MIROC-INTEG-LAND. In general, increase (decrease) in food cropland area leads to increase (decrease) in water demand, due to the increase (decrease) in irrigated cropland area (Yokohata et al. 2020). As shown in Figure 4a, food cropland area expands in the second half of the 21st century due to the lower crop yields, especially under the RCP8.5 scenario. As a result, water demand is projected to increase, especially under the RCP8.5 scenario for SSP3, where the demand for food crops is substantially high. On the other hand, SSP1 is projected to suppress the expansion of cropland area, leading to reduced irrigation water demand.

Figure S7 shows the spatial distribution of changes in water demand for irrigation estimated using MIROC-INTEG-LAND. Water demand for irrigation is considered only in food cropland area, and the irrigation ratio (ratio of irrigated cropland area to total cropland area) of each grid cell is fixed at the value of the base year (2006). Under SSP1, the demand for irrigation water is projected to decrease in India and China due to the decrease in food cropland area. Under SSP2 and SSP3, the demand for irrigation water is projected to increase in India and China, where the food cropland area is increased, as shown in Figure 4a.

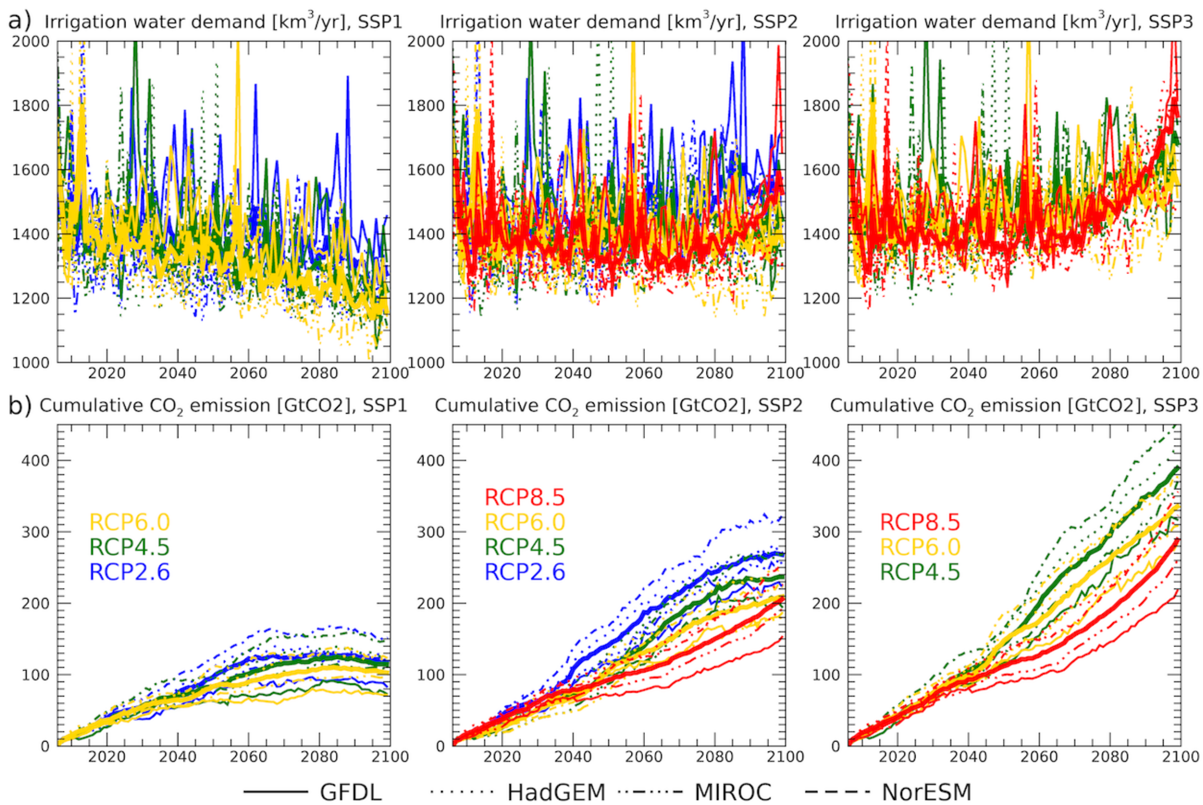

Figure 7. a) Time sequence of irrigation water demand. The unit is the global total annual irrigation water demand (unit is km^3/year); b) cumulative CO_2 emissions due to changes in land use (unit is $GtCO_2$, 10^{15} kg of CO_2). The cumulative values of the amount of CO_2 emitted in each year are shown. Line colors and styles are the same as those in Figure 3.

Figure 7b shows the cumulative CO_2 emissions due to changes in land use estimated by the ecosystem sub-model VISIT. The cumulative CO_2 emissions due to the land use change were estimated using the difference in land carbon content between the experiments with land use change and those with fixed land use in the year 2005. Changes in land use are projected to reduce net carbon sinks in terrestrial ecosystems. As shown in Figure 7b, SSP1 suppresses the expansion of agricultural land, so cumulative CO_2 emissions can be kept relatively low regardless of the climate scenario. The cumulative CO_2 emissions by 2100 due to land use change under SSP1 are approximately 100 $GtCO_2$. On the other hand, under SSP2 and SSP3, the cumulative CO_2 emissions due to changes in land use are projected to be larger compared to SSP1. Not only under RCP2.6, where aggressive mitigation measures are adopted, but also under

RCP4.5 and RCP6.0, the cropland area is projected to expand due to increased demand for bioenergy crops; as a result, cumulative CO_2 emissions increase. Overall, cropland area under SSP3 is larger than that under SSP2, which would result in higher cumulative CO_2 emissions. Cumulative CO_2 emissions by 2100 due to changes in land use are projected to be approximately 300 $GtCO_2$ under SSP2 (RCP2.6) and up to about 400 $GtCO_2$ under SSP3 (RCP4.5). According to the 6the Assessment report by Working Group 1 of Intergovernmental Panel for Climate Change, the remaining carbon budget limiting global mean surface air temperature rises to 1.5 and 2°C from pre-industrial levels with a 50% probability are 500 and 1350 $GtCO_2$, respectively (Canadell et al. 2021). The cumulative CO_2 emissions associated with land use change as shown in Figure 7b thus have a significant impact on the achievement of these climate stabilization targets.

Figure S8 shows the spatial distribution of cumulative CO_2 emissions from land use change simulated by MIROC-INTEG-LAND. The spatial distribution in Figure S8 is essentially similar to the changes in the sum of food and bioenergy cropland area shown in Figure S6. CO_2 emissions associated with land use change are higher under SSP2 and SSP3 than under SSP1, and are higher in Central Africa, South America, and North America.

4.5 Impacts of CO_2 fertilization effects and climate change

In this subsection, the impacts of CO_2 fertilization effects and climate change on food crop yields, cropland area, irrigation water demand, and CO_2 emissions associated with land use changes are discussed. We also discuss the differences in food cropland areas estimated using MIROC-INTEG-LAND and AIM/Hub, as shown in Figures 4-6.

Figure 8a shows the crop yields of experiments where the climate condition is fixed (noCL+FE, using the 2006 value), those where the CO_2 fertilization effect is fixed (CL+noFE), and those where both of the climate condition and CO_2 fertilization effect are variable (CL+FE). In all experiments, the increase in crop yields due to technological developments (Sakurai et al. 2014) is considered. Note that the results of CL+FE are the same as those shown in Figure 3.

As shown in Figure 8a, the crop yields in the noCL+FE experiments are higher than those in the CL+FE experiments due to the absence of climate change impacts. Similarly, in the

CL+noFE experiments, the crop yields are smaller than those in the CL+FE experiment, because there is no CO_2 fertilization effect. Figure 8 shows that the decrease in crop yields due to climate change (climate impact: difference between CL+FE and noCL+FE, negative value) and the increase in crop yields due to the CO_2 fertilization effects (CO_2 impact: difference between CL+FE and CL+noFE, positive value) are comparable to those estimated by MIROC-INTEG-LAND. The climate impacts are larger than the CO_2 impacts in scenarios with high CO_2 concentrations, such as the RCP8.5 scenario, leading to a decrease in crop yields in the second half of the 21st century.

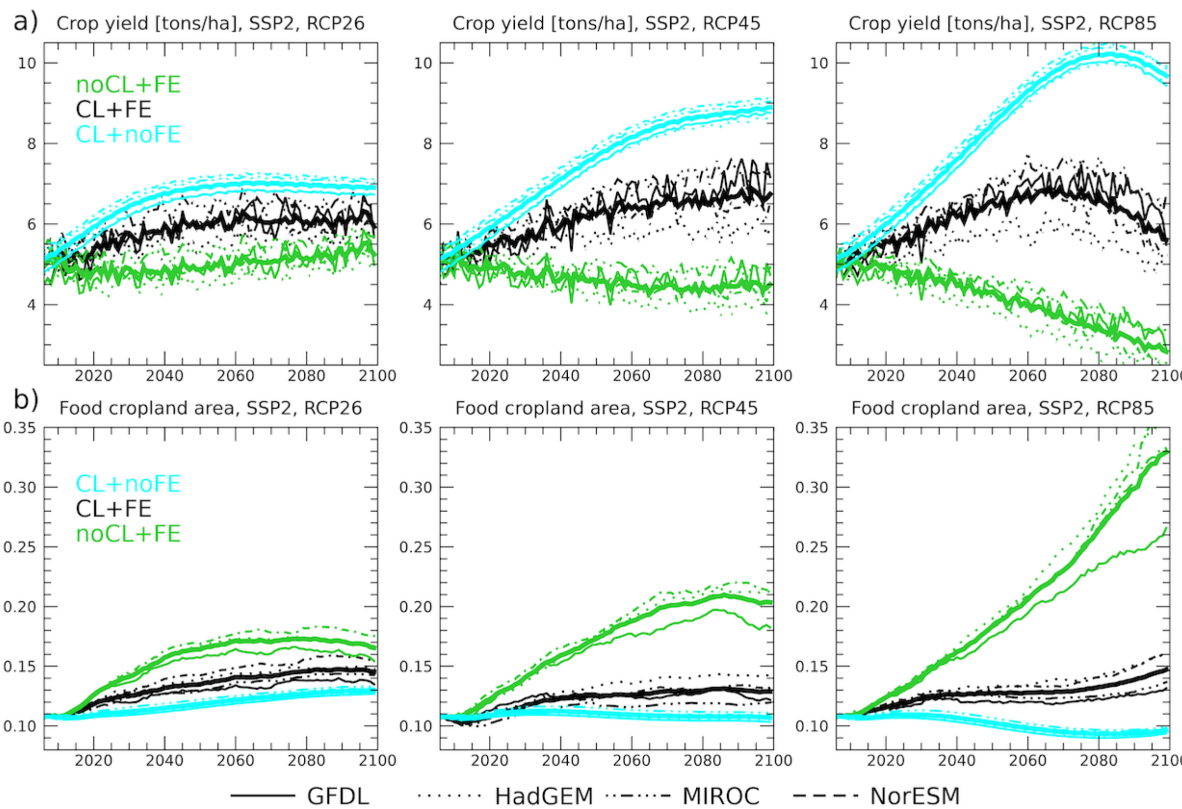

Figure 8. Time sequence of a) crop yield (unit is t/ha) and b) food cropland area (unit is ratio to the global land area) in the experiments where the climate conditions are fixed at the year 2006 (noCL+FE: green), CO_2 fertilization effect is fixed (CL+noFE: cyan), and the impacts of climate change and CO_2 fertilization effect are considered (CL+FE: black).

Figure 8b shows the results of the food cropland area in the noCL+FE, CL+noFE, and CL+FE experiments. Consistent with the results shown in Figure 8a, the cropland areas in the noCL+FE experiment are smaller than those in the CL+FE experiments due to the higher crop yields, and the cropland areas in the CL+noFE experiment are larger than those in the CL+FE experiment due to the lower crop yields. Interestingly, the absolute impacts of climate and CO_2 on food crop yields are similar, but their impacts on food cropland areas are different. This is because the food cropland area is generally inversely proportional to the food crop yields (see details in Supporting Information Text).

Previous studies on the future impact of climate change on crop yields, land use changes, and agricultural sectors have not considered the CO_2 fertilization effects (CL+noFE) (Nelson et al. 2014, Wibe et al. 2015, Mijl et al. 2018, Hasegawa et al. 2015, 2018, 2021). As shown in Figure 8, in MIROC-INTEG-LAND, the CO_2 fertilization effect has comparable impact on crop yields as that of climate change. Therefore, if the CO_2 fertilization effect is not taken into consideration, the crop yield tends to be underestimated. Therefore, in a scenario with a large CO_2 concentration increase such as under RCP8.5, not clarifying whether experiments were performed 'with' or 'without' the CO_2 fertilization effect (CL+noFE and CL+FE) can result in overestimating the future land use changes and their uncertainty ranges.

The food cropland areas simulated by AIM/Hub (Figure 4) do not consider the impacts of climate change and CO_2 fertilization effects. Under the RCP2.6 and RCP4.5 scenarios, the climate and CO_2 impacts on food crop yields are almost compensated for in MIROC-INTEG-LAND (Figure 8). Therefore, the reason why the cropland areas estimated by AIM/Hub are smaller than those estimated by MIROC-INTEG-LAND are due to differences in technological development or the effects of bioenergy demands which have the effect of increasing the food crop yields in AIM/Hub. On the other hand, under the RCP8.5 scenario, the impacts of climate change decrease estimates of food crop yields in MIROC-INTEG-LAND, as the contribution of climate change outweighs the CO_2 fertilization effects in the second half of the 21st century, as shown in Figure 8. One of the reasons why the cropland areas estimated by AIM/Hub are smaller than those estimated by MIROC-INTEG-LAND under the RCP8.5 scenario is because climate change is projected by the latter model to reduce food crop yields.

Finally, Figure 9 shows the water demand for irrigation and cumulative CO_2 emissions associated with land use changes in the noCL+FE, CL+noFE, and CL+FE experiments. In the absence of the CO_2 fertilization effect (CL+noFE), the food cropland area increases due to a decrease in the crop yield, resulting in an increase in water demand for irrigation and CO_2 emissions associated with land use change. The results in Figure 9 show that the impacts of CO_2 fertilization effects and climate change play an important role in future changes in water demand and cumulative carbon emissions through the changes in cropland area.

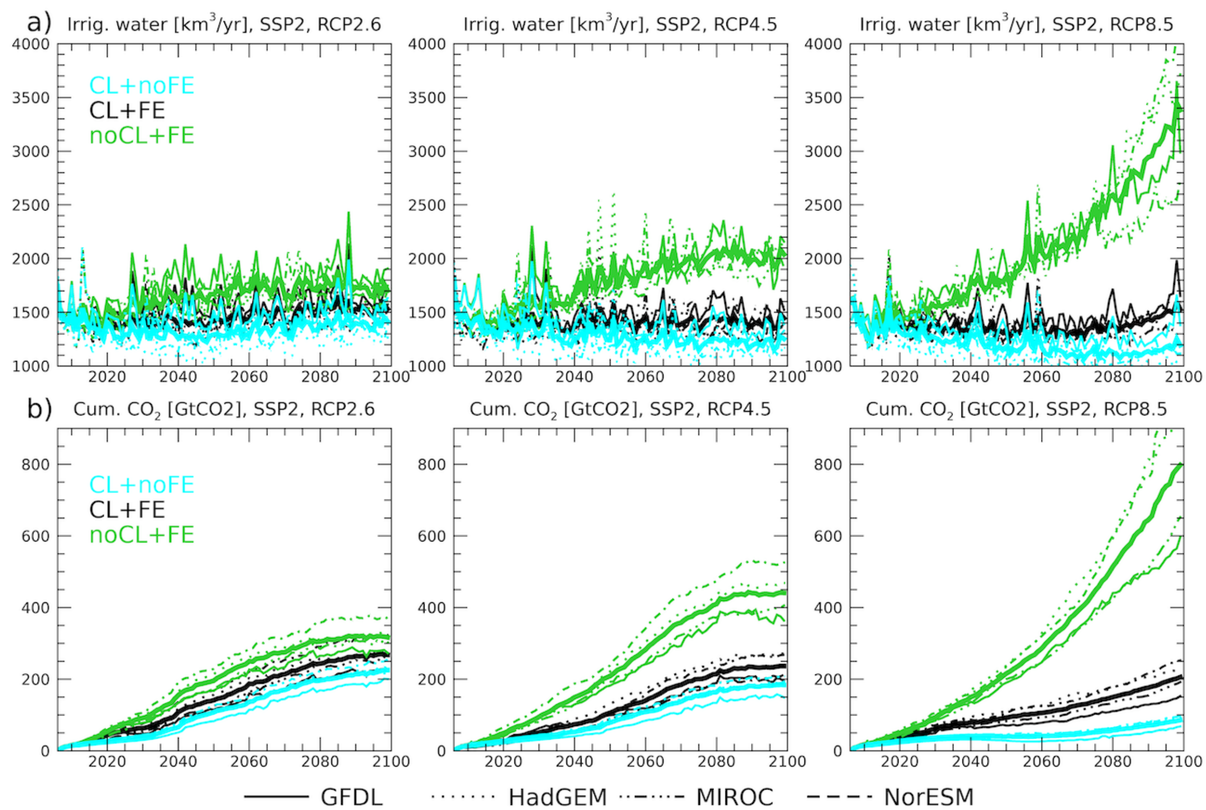

Figure 9. Same as Figure 8, but for a) the water demand for irrigation (unit: km^3/year), and b) cumulative CO_2 emissions due to land use changes (unit: $GtCO_2 = 10^{15}$ kg of CO_2).

5 Conclusions

This study evaluated the impact of the combination of future socio-economic and climate changes on water resources, crop growth, land use and ecosystems. Future food crop yields are projected to increase, primarily due to CO_2 fertilization effects and technological developments;

however, they are projected to decrease when surface air temperatures rise substantially. Future changes in food crop yields and demands are projected to affect changes in food cropland areas. In addition, increasing demand for bioenergy crops for climate change mitigation can also lead to the expansion of bioenergy cropland areas.

Under the sustainability scenario (SSP1), increases in cropland area are kept small due to low demand for food and bioenergy crops. On the other hand, under the middle of the road (SSP2) and regional rivalry (SSP3) scenarios, the demand for food and bioenergy crops is higher than that under SSP1, so the increase in these cropland areas is large. In general, the contributions of bioenergy cropland to total cropland area are projected to be substantial under the RCP2.6, RCP4.5, and RCP6.0 scenarios, while those from food cropland are dominant under the RCP8.5 scenario. The expansion of food and bioenergy cropland areas is projected to increase water demand for irrigation and CO_2 emissions associated with land use change. It is important to create a green society, such as that envisaged under SSP1, by reducing the demand for food and bioenergy and promoting technological innovations, in order to reduce CO_2 emissions due to land use changes and to protect biodiversity.

Our analysis showed that the impacts of CO_2 fertilization effects and climate change on crop yields are generally comparable, with the latter being larger than the former when the increase in GHG concentrations are large such as under the RCP8.5 scenario. Our results also showed that the CO_2 fertilization effects and climate change play a very important role in food cropland areas, water demand for irrigation, and CO_2 emissions due to land use change. Therefore, when the CO_2 fertilization effect is ignored, the food cropland areas are greatly overestimated, especially under scenarios where the increase in CO_2 concentrations is large. To improve the accuracy of projecting these impacts on the global system, it is important to increase current knowledge about the CO_2 fertilization effects as well as the impacts of climate change on crop yields (Ainsworth and Long 2005, Erda et al. 2005, Sakurai et al. 2014, Degener 2015, McGrath and Lobell 2013, Wang et al. 2020).

The socio-economic scenarios adopted in CMIP6 do not consider the impacts of climate change and CO_2 fertilization effects on crop yields when projecting future land use change (Riahi et al. 2017, O'Neil et al. 2017, van Vuuren et al. 2017, Fricko et al. 2017, Fujimori et al. 2017). The results obtained using MIROC-INTEG-LAND show that the expansion of cropland area is larger than that estimated using AIM/Hub, which does not consider the impacts climate change and the CO_2 fertilization effect. This difference between the two models is caused by the impacts of climate change, especially under scenarios with high GHG concentrations, such as RCP8.5. The results of this study demonstrate the importance of considering the interactions between Earth and human systems when constructing future socio-economic and climate scenarios.

Acknowledgments and Data

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Conflict of Interest

The authors have no competing interests to declare.

Data Availability Statement

The MIROC-INTEG-LAND source code for this study is available for purposes of collaborative research with the model users under license from the copyright holders. For further information on how to obtain the code, please contact the corresponding author. The data from the model simulations and observations used in the analyses are available from the corresponding author.

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Earth's Future

Supporting Information for

Impacts of socio-economic and climate changes

on water, food, bioenergy, land use, and ecosystems

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Additional Supporting Information (Files uploaded separately)

Text S1. The impacts of climate and CO2 on food crop yields and cropland area

As shown in Figure 8, the absolute impacts of climate and CO2 on food crop yields are similar, but their impacts on food cropland areas are different. This is because the food cropland area is generally inversely proportional to the food crop yields. Let Y_0 be the crop yield of the CL+FE experiment, $Y_0 + Y_{CL}$ be the crop yield of the noCL+FE experiment, and $Y_0 - Y_{FE}$ be the crop yield of the CL+noFE experiment. Here, Y_{CL} and Y_{FE} represent the contributions of the climate change and the CO_2 fertilization effect on the crop yield, respectively (both positive values). Assuming that the food cropland areas of the CL+FE, noCL+FE, and CL+noFE experiments are A_0, A_{CL}, and A_{FE}, respectively, then the ratio of each cropland area is as follows.

$$A_{CL}/A_0 \sim Y_0/(Y_0+Y_{CL})=(1+Y_{CL}/Y_0)^{-1}$$

$$A_{FE}/A_0 \sim Y_0/(Y_0-Y_{FE})=(1-Y_{FE}/Y_0)^{-1}$$

If the contributions of climate change and the CO_2 fertilization effects are very small (Y_{CL}/Y_0, Y_{FE}/Y_0 approach to zero),

$$A_{CL}/A_0 \sim 1,$$

$$A_{FE}/A_0 \sim 1.$$

On the other hand, if the contributions of climate change and the CO_2 fertilization effect are large enough, that is, if Y_{CL}/Y_0 and Y_{FE}/Y_0 approach to 1, then

$$A_{CL}/A_0 \rightarrow 1/2,$$

$$A_{FE}/A_0 \rightarrow \infty.$$

Therefore, the contribution of CO_2 fertilization effects on food cropland area (A_{FE}) is relatively large compared to that of climate change (A_{CL}). For example, if the food crop yields in 2100 under the RCP8.5 scenario are $Y_0 = 5.5$, $Y_{CL} = 4.0$, $Y_{FE} = 3.0$ [t/ha], then the changes in food cropland area can be estimated as $A_{CL}/A_0 \sim 0.57$ and $A_{FE}/A_0 \sim 2.2$ by using the above equations. This estimation corresponds to a decrease in A_{CL} by approximately 43%, A_{FE} increases by approximately 120%, which is generally consistent with the results shown in Figure 9. In other words, even if the climate and CO_2 impacts on crop yields (Y_{CL} and Y_{FE}) are comparable, their effects on changes in cropland areas (A_{CL}-A_0 and A_{FE}-A_0) are relatively larger in the latter case compared to the former case.

Table S1. The characteristics of the SSP scenarios adopted from O'Neil et al. 2017.

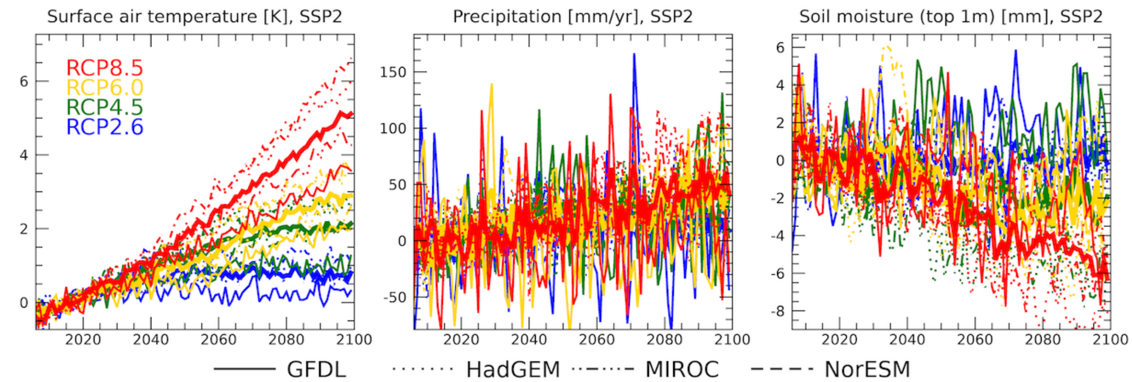

Figure S1. Time sequence of anomalies in surface air temperature (left, unit is K), precipitation (middle, unit is mm/year), and volumetric soil moisture content (right, unit is mm in top 1m). The baseline of anomaly is the 20-year average from 2006-2025. The surface air temperature and precipitation are used as the input for the model, and other variables are calculated by MIROC-INTEG-LAND. Global average (surface air temperature) and average for global land area (precipitation, soil moisture) are shown. The line colors show the results obtained under the RCP2.6 (blue), RCP4.5 (green), RCP6.0 (yellow), and RCP8.5 (red) scenarios. Thin lines are the results obtained from four GCMs, and thick lines are the average values obtained from four GCMs.

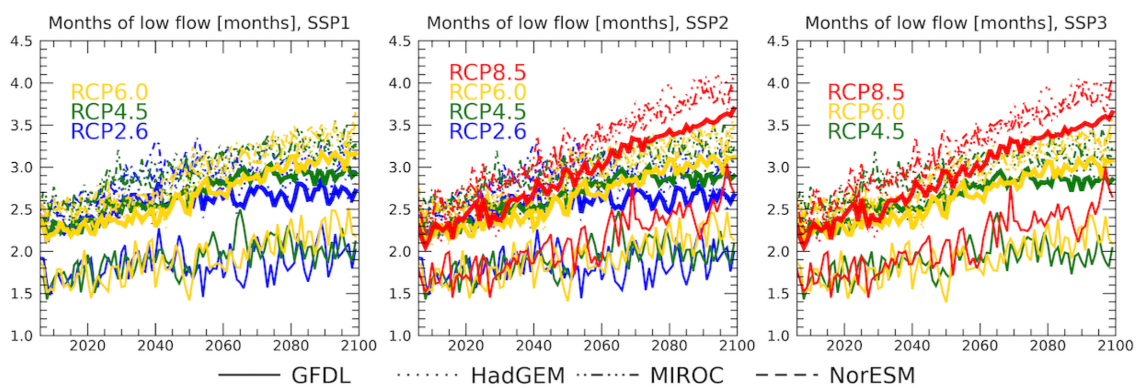

Figure S2. Time sequence of the number of drought months calculated by MIROC-INTEG-LAND. The average results over the global land area are shown. Drought months are defined as the number of months with river flows below the 20 percentiles for each month in historical experiments (1950-2005). If the number of drought months is 3, it means that there are 3 months in the year with river flows below the 20

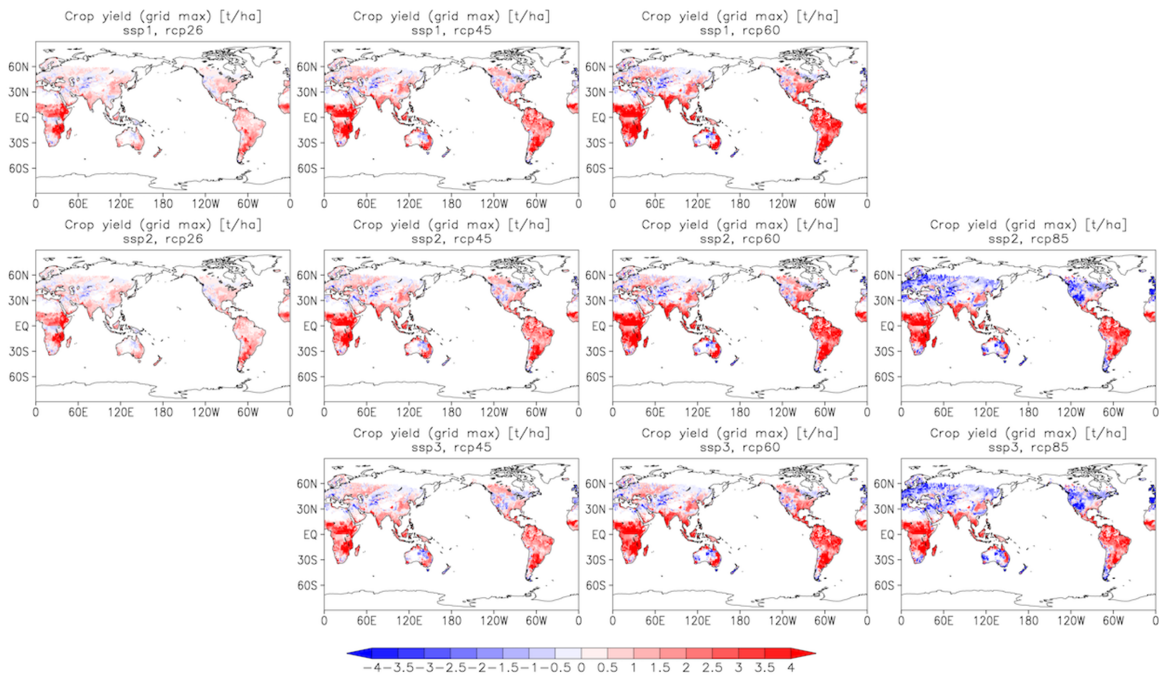

Figure S3. Global map showing anomalies in crop yields (unit is tons/ha). The anomalies are calculated by the difference between the averages of 2081-2100 and 2006-2025. Crop yield is calculated in the same way as in Figure 3.

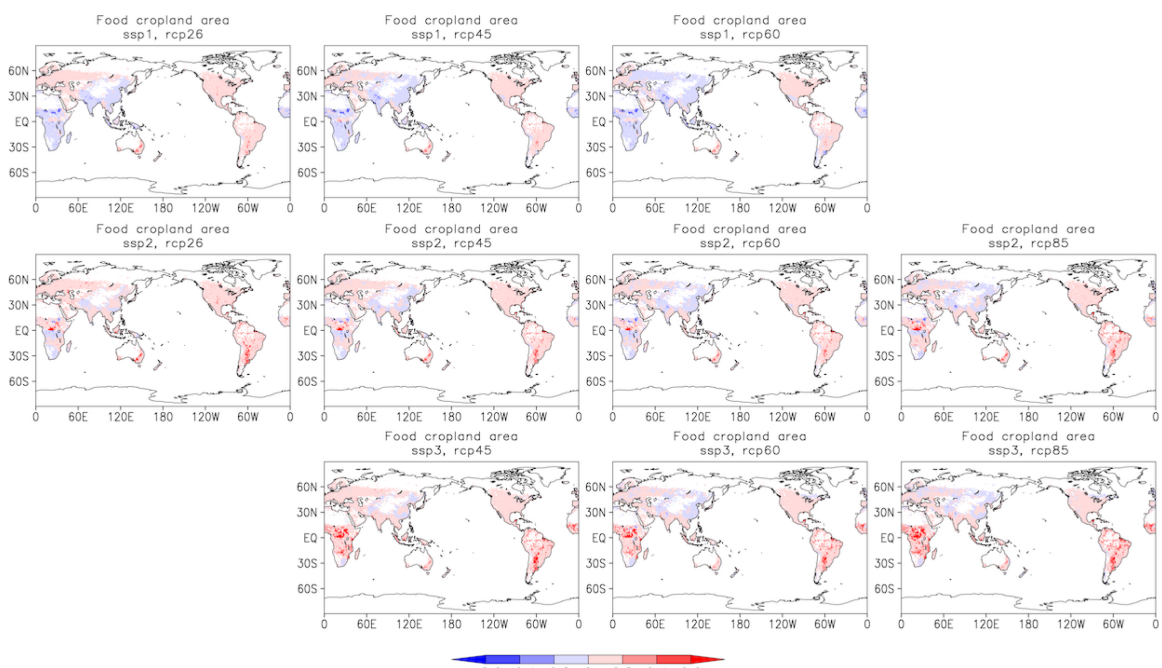

Figure S4. Same as Figure S3, but for anomalies in food cropland area. The unit is the ratio of the cropland area in each grid / total area of the grid.

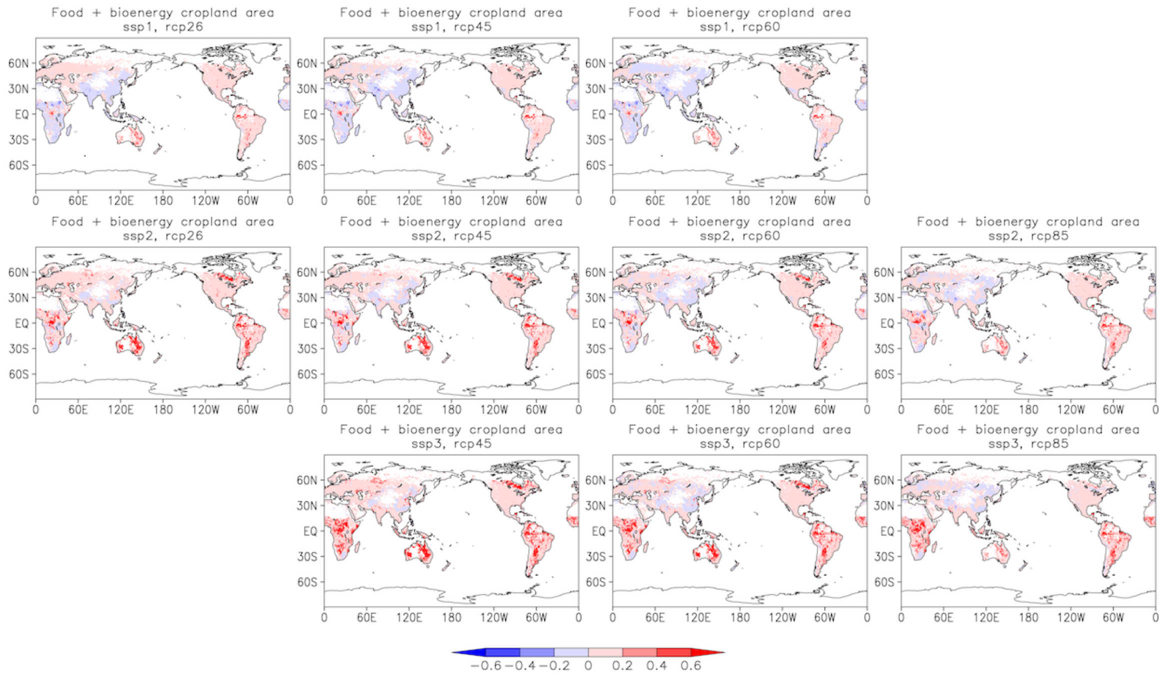

Figure S5. Same as Figure S3, but for anomalies in bioenergy cropland area. The unit is the same as that in Figure S4.

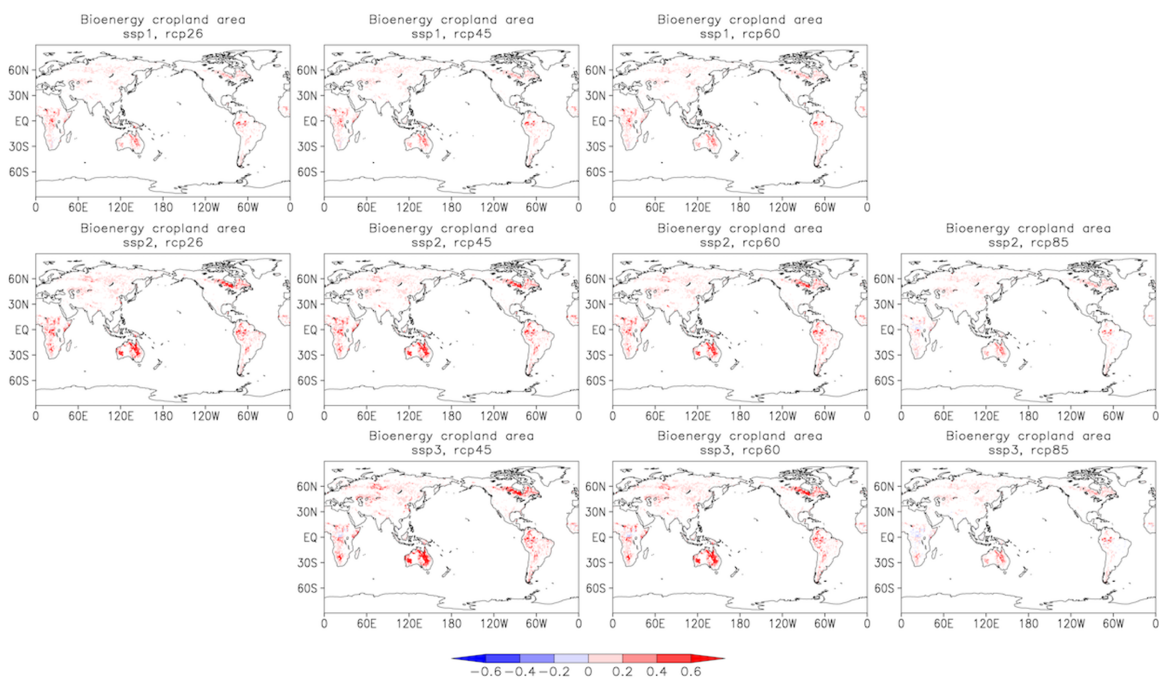

Figure S6. Same as Figure S3, but for anomalies in bioenergy cropland area. The unit is the same as that in Figure S4.

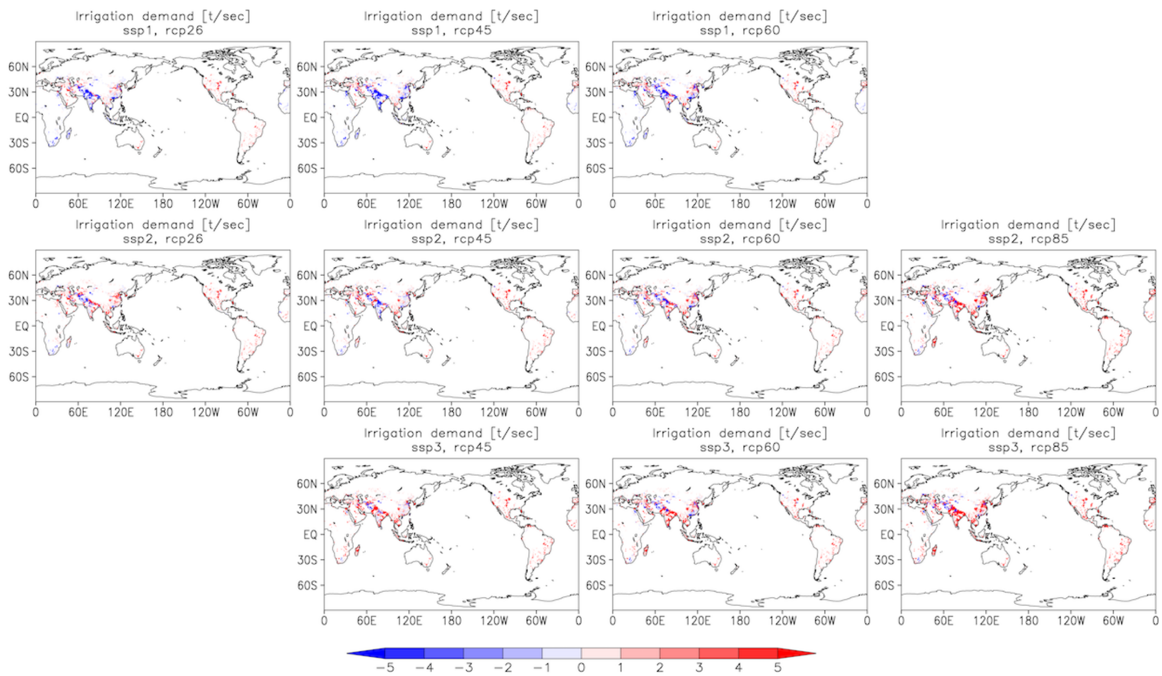

Figure S7. Same as Figure S3, but for anomalies in water demand for irrigation. The unit is kg/sec in each grid (1° longitude and latitude).

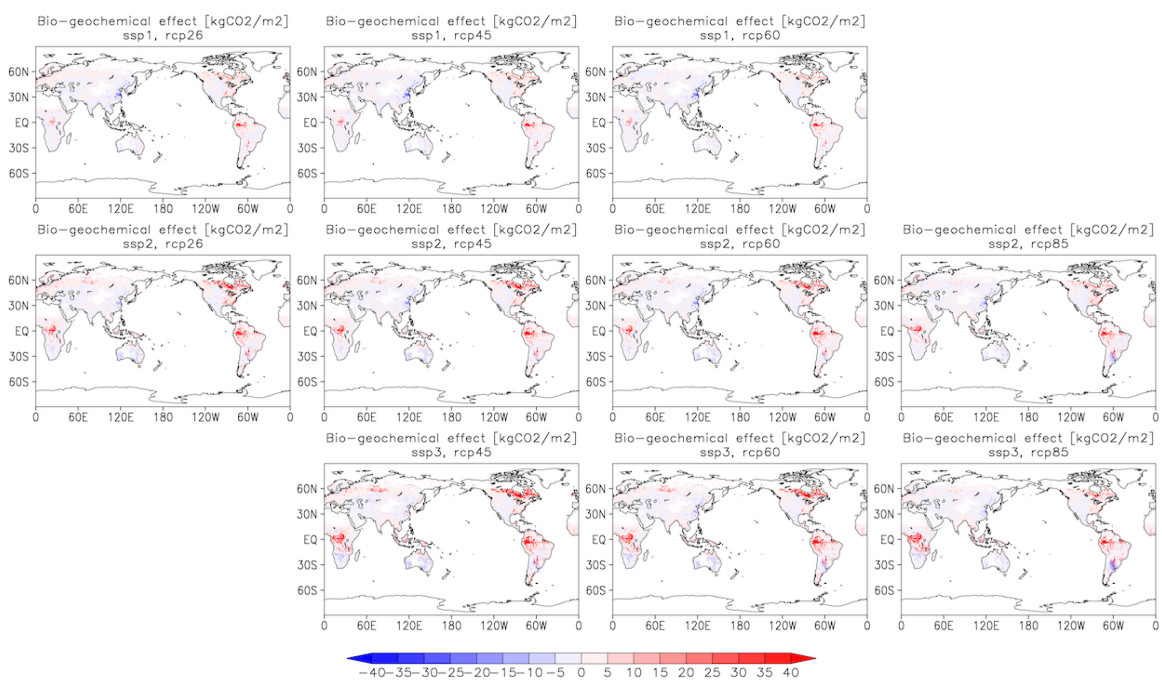

Figure S8. Time Cumulative CO_2 emissions due to land use change. The cumulative emission from 2006 to 2100 is shown. The unit is $kgCO_2/m^2$.