



# Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6)

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## Abstract

Negative emission technologies such as bioenergy with carbon capture and storage (BECCS) are regarded as an option to achieve the climatic target of the Paris Agreement. However, our understanding of the realistic sustainable feasibility of the global lands for BECCS remains uncertain. In this study, we assess the impact of BECCS deployment scenarios on the land systems including land use, water resources, and ecosystem services. Specifically, we assess three land-use scenarios to achieve the total amount of 3.3 GtC year<sup>-1</sup> (annual negative emission level required for IPCC-RCP 2.6) emission reduction by growing bioenergy crops which requires huge use of global agricultural and forest lands and water. Our study shows that (1) vast conversion of food cropland into rainfed bio-crop cultivation yields a considerable loss of food production that may not be tolerable considering the population increase in the future. (2) When irrigation is applied to bio-crop production, the bioenergy crop productivity is enhanced. This suppresses the necessary area for bio-crop production to half, and saves the land for agricultural productions. However, water consumption is doubled and this may exacerbate global water stress. (3) If conversion of forest land for bioenergy crop cultivation is allowed without protecting the natural forests, large areas of tropical forest could be used for bioenergy crop production. Forest biomass and soil carbon stocks are reduced, implying degradation of the climate regulation and other ecosystem services. These results suggest that without a careful consideration of the land use for bioenergy crop production, a large-scale implementation of BECCS could negatively impact food, water and ecosystem services that are supporting fundamental human sustainability.

**Keywords** BECCS · Land use · Water resources · Ecosystem service · Sustainability

## Introduction

In December 2015, the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the “Paris Agreement” that stipulates “holding the increase in the global average temperature to well below 2 °C above pre-industrial levels” (Article 2). Considering the risk of crossing the dangerous tipping point of abrupt and irreversible change above a certain temperature (Schellnhuber et al. 2016; Schleussner et al. 2016), this “2 °C target”, or even “1.5 °C target” if possible, is internationally agreed as a very important global common goal to achieve.

In fact, from a scenario point of view, “2 °C target” corresponds to the IPCC Representative Concentration Pathway (RCP) 2.6 scenario (van Vuuren et al. 2011). According to the underlying scenarios corresponding to the RCP2.6 scenario, it is supposed that the global total carbon emission

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(human emissions minus natural absorption) will go negative near the end of this century (Fuss et al. 2014).

On the other hand, regarding more comprehensive global sustainability, heads of the states also agreed on yet another very important treaty in the same year. Namely, on September 25, 2015, the United Nations adopted the “Sustainable Development Goals (SDGs)” which demand all the UN countries to make all the possible efforts to end poverty, protect the planet, and ensure prosperity for all as part of a new sustainable development agenda. Although the 17 SDG compliances are voluntary, each goal has specific targets (measured by corresponding indicators) to be achieved by 2030. Actually, “Climate action” is the 13th goal of the 17 SDGs. So, the climate change mitigation policy (until 2030) of the Paris Agreement is a part of SDGs. Under the SDGs, it is recommended that the governments should achieve all the goals at the same time. However, in fact, there are trade-offs and synergies between the goals. So, we need to understand the interactions between the goals to come up with a better scenario to achieve the SDGs. This is the background why we need to study the impact of climate change mitigation on other types of sustainability such as water, food and ecosystems.

Considering the cumulative emission of anthropogenic greenhouse gases (GHGs) until today and projected emissions accompanying human activities in the future (Creutzig et al. 2016), it is quite challenging to achieve the “2 °C target” by only reducing GHGs. In this regard, bioenergy with carbon capture and storage (BECCS) is highlighted as a promising “Negative Emission” technology, which allows us both to earn more carbon-neutral energy and reduce atmospheric CO<sub>2</sub> concentrations at the same time (Smith et al. 2016). The technology would produce electricity by bioenergy combustion, then capture CO<sub>2</sub> emissions and store it into deep ground.

However, producing a massive amount of bioenergy crop requires the vast use of agricultural cropland. Smith et al. (2016) estimated that the mean land requirement for BECCS would be 380–700 × 10<sup>6</sup> ha in 2100. The land requirement would be partly suppressed by enhancing agricultural productivity by irrigation. Hejazi et al. (2015) projected the total water use in the USA under a stringent GHG emission reduction policy. They found that the policy could increase water stress more than the climate change itself mainly due to bioenergy irrigation. Bonsch et al. (2016) estimated how much land and water was required to produce 300 EJ year<sup>-1</sup> of bioenergy. They found that 486 × 10<sup>6</sup> ha of cropland and 3000 km<sup>3</sup> year<sup>-1</sup> of irrigation water withdrawal were needed. In case no irrigation was applied, 41% of cropland was additionally required (total 689 × 10<sup>6</sup> ha).

Although the abovementioned two studies have quantified the trade-offs between mitigation and water scarcity, and land and water, respectively, further investigation is needed

to explore whether irrigation water is stably and sustainably available. From the perspective of its impact on land use and ecosystem services, deployment of BECCS may have ramifications such as loss of biodiversity, deterioration of water quality, and additional emissions of nitrous oxide into the atmosphere (Melillo et al. 2009; Smith et al. 2016). Expansion of plantation of bioenergy crops (e.g., oil-palm) would exert influence on the atmospheric quality by emitting volatile organic compounds (Miształ et al. 2011). However, our knowledge on the direct and indirect impact of BECCS on ecological systems is far from sufficient to conduct a reliable evaluation and to plan feasible management.

To fill the gap of the knowledge required from the urgency of the need to implement climate change mitigation activities and their sufficient assessments regarding their impact on other sustainability indicators, in this paper, we used multiple models to simulate the trade-offs between water, food, and ecosystems under three different land-use scenarios to produce bioenergy crop in agricultural land with/without irrigation and in converted forest lands. Then, we assess the impact from the BECCS deployment scenarios with the total amount of 3.3 GtC year<sup>-1</sup> (annual negative emission potential required for RCP2.6; see Smith et al. 2016) of bioenergy by growing bio-crops with substantive use of global agricultural and forest lands. Especially, the effects and sustainability of irrigation for global massive production of bioenergy is investigated using the H08 global hydrological model (Hanasaki et al. 2008a, b, 2010). Finally, the impact of massive use of converted forest land is assessed using VISIT terrestrial ecosystem model (Ito and Inatomi 2012).

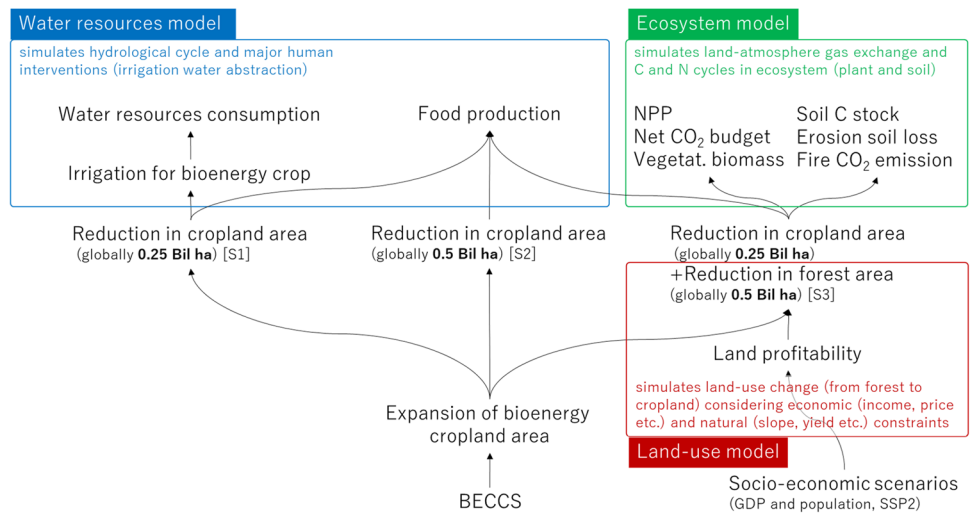
## Methods

### Overall study design

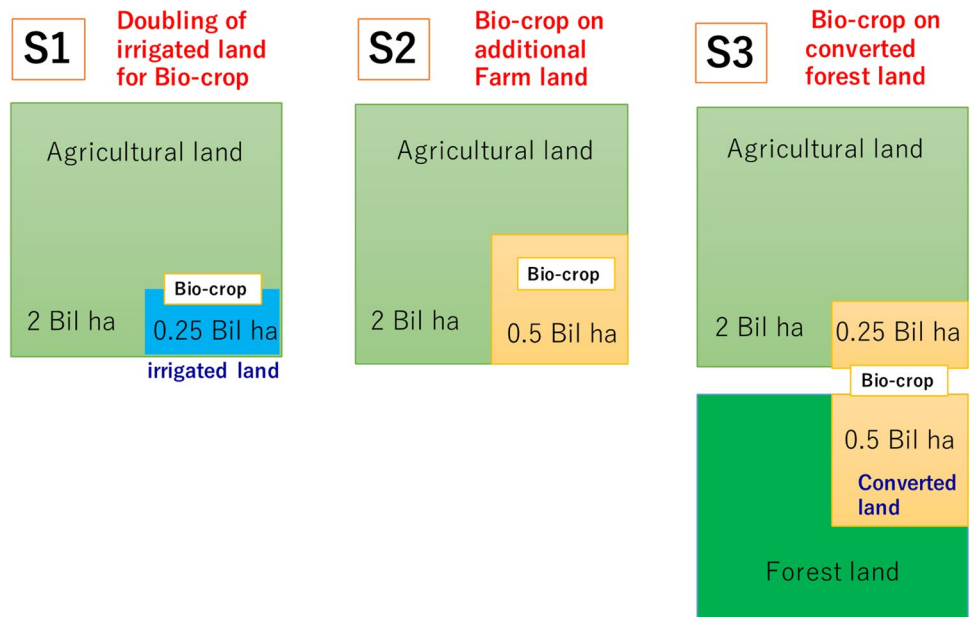
We assessed the impact of BECCS deployment scenarios on land systems including land use, water resources, and ecosystem services. Figure 1 shows the general explanation of the models used in our study and illustrates the parameters and variables exchanged between the water resources, ecosystems, and land-use models. There are some dependences between the models. For example, irrigation for bioenergy crop will decrease the renewable water resources, while land conversion for bioenergy cropland will decrease the forest area etc.

We assessed three land-use scenarios (Fig. 2) to achieve the annual emission reduction of 3.3 GtC year<sup>-1</sup> (required for IPCC-RCP 2.6). We based on the cropland scenario of Harmonized Global Land Use (Chini et al. 2014) for RCP2.6. It projects that the global total cropland area reaches 2.12 billion ha in 2100. Since this scenario does not specify the land used for food and bioenergy production,

**Fig. 1** Explanation of the models used to assess the impact of different land-use scenarios and interactions between the model parameters and variables. They are used to project situations in 2100



**Fig. 2** Land-use scenarios for bioenergy crop production for RCP2.6 in 2100



we assumed 0.5 billion ha is required to achieve 3.3 GtC of BECCS (here after the S2 scenario). It indicates that the cropland for food production would be 1.62 billion ha, or approximately 10% larger than the present areal extent. It would be desired to save the cropland for food from the view point of food security, however, because difficult food supply and demand condition would be expected due to negative consequence of climatic change impact on food production, population growth, economic boost, and intensified interannual variations in the future climate. Here we consider two additional scenarios, namely, saving 0.25 billion ha of food cropland by intensive irrigation for bioenergy crop (the S1 scenario) and additional deforestation (S3; Fig. 1).

In the case of S2, very large areas (500 million ha, or up to 25% of the global farm lands) are used for bioenergy

crop production (rainfed) all over the world. On the other hand, in the case of S1, the demand for farm lands is relaxed by assuming that bioenergy crop is irrigated to increase productivity to reduce the required land into half. In the case of the S3 scenario, large natural lands (500 million ha, or up to 10% of the total current forest land area) are assumed to be converted into bioenergy crop lands. Here we consider two sub-scenarios: (S3-1) no reserved area, allowing conversion of high biodiversity tropical forests, and (S3-2) biodiversity hotspots are reserved on the basis of the map by World Wide Fund for Nature. We expect that assessing such typical scenarios is effective to clarify the potential impact and risks, and that reality may lay around the intermediate between the scenarios. For creating these scenarios, we used a land-use model which

calculates the land productivity for growing crops with allocation of the necessary areas for conversion.

Using these S1, S2, S3 land-use scenarios, the models described in Fig. 1 were used to analyze the impact for sustainability of land-use scenarios under RCP 2.6 from the perspectives of ecosystem and water resource in the future. In the land-use modeling, the suitability of bioenergy crop cultivation was estimated in a similar manner to other food crops (i.e., wheat and maize) for simplicity. The base cropland area used in future land-use scenario S1 (with irrigation) and S2 (without irrigation) in 2000 was derived from harmonized global land use (Chini et al. 2014) which is consistent with RCP 2.6 (van Vuuren et al. 2011) and cropland expansion for BECCS was assumed to occur in the twenty-first century at a constant rate. The scenario S3 in which forests are consumed for bio-crop production was derived from a land-use model including socio-economic factors.

The scenario of spatial distribution of forest transferred into cropland for bioenergy was developed based on the profitability of agriculture. Profitability was estimated in each 30 arc-second grid cell and it was calculated by a linear regression model whose explanatory variables were wage, slope angle of land, bio-crop price and bio-crop yield. Wage and bio-crop price were the same in all the grid cells which belonged to regions which were defined by the socio-economic scenario, and slope angle in each 30 arc-second grid cell was given by GTOPO30 (available from USGS). The spatial distribution of bio-crop yield was given by downscaling the results of a model whose resolution was half-degree grid cell. We assumed that bioenergy crops such as miscanthus and switchgrass would be used and their yields were estimated by a model (Kato et al. 2013). The socio-economic scenario such as wage and crop price used in this model was provided by the Asia-Pacific Integrated Model (Fujimori et al. 2014). Parameters were estimated using productivity of the existing crop lands. It was also assumed that the spatial distribution of cropland for food and pasture land would not change from 2000.

Simulations were conducted using the climate scenario developed for the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; Hempel et al. 2013). We used scenarios for the MIROC-ESM-CHEM Earth System Model (Watanabe et al. 2011) under the RCP2.6 scenario (van Vuuren et al. 2011). The MIROC-ESM-CHEM tends to give a high warming trend, making it easy to assess possible climate impact. Nevertheless, the magnitude of warming in the twenty-first century under RCP2.6 scenario (about 2.3 K land-average) was comparable with the other climate models. We selected the climate projection as a representative and a comparison among the different climate scenarios is remaining for our forthcoming study. The data cover the whole globe at a spatial distribution of  $0.5^\circ \times 0.5^\circ$  and the period of 1960–2100 at a daily interval.

## Water resource model

The H08 model is a physically-based global hydrological model (Hanasaki et al. 2008a, b, 2010). It simulates basic hydrological components globally at  $0.5^\circ \times 0.5^\circ$  spatial resolution by solving the energy and water balance at land surface. H08 explicitly expresses major human interventions in the natural hydrological cycle, namely, water abstraction for irrigation, industrial, and domestic use, and reservoir operation of major dams. All the natural and human processes interact at a daily interval.

H08 incorporates sub-models to estimate the potential crop yield, the cropping calendar, and irrigation water requirement for annual food crops, but not for perennial bioenergy crops. These sub-models that were enhanced to deal with giant miscanthus (*Miscanthus giganteus*) and switchgrass (*Panicum virgatum*) which are both the so-called second-generation bioenergy crops are explained as follows. First, the crop-specific parameters for miscanthus and switchgrass were added to the crop yield sub-model which were taken from the SWAT model version 2012 (Arnold et al. 2012). Next, the cropping calendar sub-model was enhanced to deal with perennial plants. The growing period was estimated by searching the longest continuous days above the base air temperature ( $10^\circ\text{C}$  for miscanthus and  $12^\circ\text{C}$  for switchgrass) in a year. If it exceeded 300 days, the continuous 300 days which produced the maximum mean yield was selected. Irrigation water was applied to keep soil moisture above 75% of the field capacity during the cropping period. Note that these sub-models are independent from that of Kato et al. (2013) which was used to develop the land-use scenarios: the sub-models are tightly incorporated into the H08 model and it was unable to replace them with Kato et al. (2013). In H08, soil moisture (or water and energy balance) is calculated for each land use. The standard H08 subdivides a grid cell into four different land uses, namely double-crop irrigated food cropland, single-crop irrigated food cropland, rainfed food cropland, and non-agricultural land. We newly added two land uses for irrigated and rainfed bioenergy cropland.

Using the enhanced H08, three simulations were conducted. The first simulation was the base simulation. The simulation period is 1996–2005. It assumed no production of massive second-generation bioenergy crop in this period. The H08 simulated the natural hydrological cycle and human water use using the present spatial distribution of irrigated and rainfed cropland. The second simulation assumed that 250 million ha of cropland was changed into irrigated bioenergy cropland by 2100 (Scenario S1). The simulation period is 2006–2100. Irrigation water was primarily taken from the rivers in the same grid cell. We estimated how much additional water was required when the rivers were depleted. The third simulation assumed

that 500 million ha of cropland was changed into rainfed bioenergy cropland by 2100 (Scenario S2). The boundary conditions given to H08 were identical to those of Hanasaki et al. (2013a, b). Irrigated cropland area, and crop type were obtained from Siebert et al. (2005) and Monfreda et al. (2008), respectively, and fixed throughout the simulation period. In this study, the effects of CO<sub>2</sub> fertilizer were not considered. It was expected that crop yield would grow by time due to technological advancement, so that effect was not considered either.

## Ecosystem model

The Vegetation Integrated Simulator for Trace gases (VISIT) model was used to evaluate terrestrial properties related to ecosystem services. The model is a process-based model of the terrestrial biogeochemical cycle and ecosystem dynamics (Ito and Inatomi 2012), focusing on atmosphere–ecosystem interactions under changing climate conditions. The model simulates water, carbon, and nitrogen cycles in terrestrial ecosystems using a simple box-flow framework, enabling us to apply this model to point to global scales. Particularly, this model simulates atmosphere–ecosystem exchange of trace gases such as greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O), biomass-burning emissions (e.g., CO and black carbon), and biogenic volatile organic compounds. In this study, we focused on six terrestrial properties related to ecosystem services: (1) net primary production (NPP) related to fundamental and provisional services, (2) net ecosystem CO<sub>2</sub> exchange related to regulation services, (3) vegetation biomass related to fundamental, provisional, and cultural (by scenery) services, (4) soil carbon stock related to fundamental services, (5) soil loss due to erosion and (6) biomass burning related to degradation of ecosystem services. Carbon dynamics in terrestrial ecosystems were simulated in an ecophysiological manner, such that photosynthetic carbon uptake was estimated on the basis of leaf-level gas exchange and canopy radiation transfer (Ito and Oikawa 2002). Mass balance of carbon stocks in vegetation and soil pools was estimated by accounting the carbon input and output for each of the eight carbon pools: three for C<sub>3</sub>-type vegetation, three for C<sub>4</sub>-type vegetation, and two soil organic carbon. Soil loss by water erosion was estimated using the revised universal soil loss equation, which accounts for slope, soil stability, precipitation, vegetation cover, and human management factors, and was implemented into the VISIT model (Ito 2007). Biomass burning was simulated using an empirical scheme to estimate burnt area and combustion intensity, which are functions of fuel load and soil wetness.

## Results and discussion

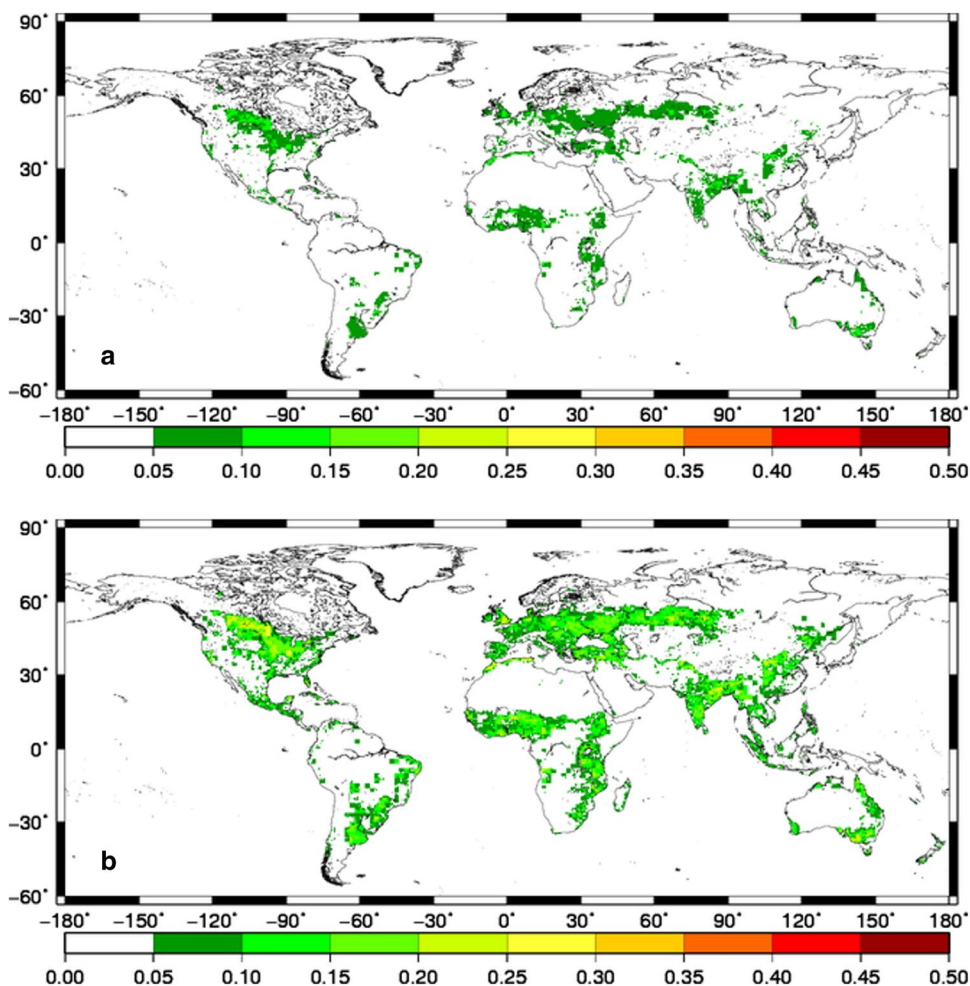
### Land-use scenarios

Figure 3 displays projected bio-crops distributions in 2100 under S1 and S3 (a), and S2 (b). This figure shows that S2 increases land for bio-crops globally. The increase is considerable especially in South Africa, North America, and Europe. Figure 4 shows the distribution under S3 with assumption of additional use of natural land without or with reserved lands. The rain forest of Brazil changed into cropland first, followed by the rain forest of Congo. The land-use scenario which was used for S3-1 does not take into account forest protection regulations such as REDD. Also, bioenergy crop lands are expected to increase in the semi-arid land in Australia and in Canada. On the other hand, if the tropical rain forests are strongly protected (S3-2), bioenergy crop land is expected to increase more in the semi-arid land in Australia and southern Africa and the boreal forest land in Canada and Russia.

### Water resource model

The results of irrigation water use for bioenergy are shown in Table 1. For Scenario S1, the volume of consumptive irrigation water use to produce bioenergy was estimated at 1910 km<sup>3</sup> year<sup>-1</sup> in 2090s (the mean of 2091–2100). This volume is as much as 135% of the volume for food production (1420 km<sup>3</sup> year<sup>-1</sup>) of the base simulation which is fairly comparable with earlier independent estimates (e.g., 1231 km<sup>3</sup> year<sup>-1</sup> in Döll et al. 2012). Irrigation water use for bioenergy was concentrated in some parts of South America, central Sahel, eastern India, and northern and southern Australia (Fig. 5). The spatial distribution reflects three aspects: the distribution of irrigated bioenergy cropland, soil moisture deficit, and length of growing period. As is explained in the Method chapter, Scenario S1 assumed that 250 million ha of cropland was converted into that for bioenergy proportional to the total cropland, hence irrigation is concentrated in the world's major breadbasket areas. Second, since irrigation was applied to maintain soil moisture above 75% of the field capacity, it tends to be concentrated in semi-arid regions. Third, since this study assumed that irrigation was applied throughout the cropping period, warm regions with long cropping period tend to require a large volume of irrigation. Of the total irrigation water requirement, rivers supplied only 1580 km<sup>3</sup> year<sup>-1</sup> of water. The remaining 1910 km<sup>3</sup> year<sup>-1</sup> should be supplied from other sources. This is mainly explained by the opposite temporal phase between river discharge and irrigation water: irrigation

**Fig. 3** Areal fraction of bio-crop farmland in 2100. **a** S1 and S3 (excluding farmland transferred from forest), **b** S2



water requirement is intensive when the soil gets drier, and the condition also restricts the runoff of the surrounding regions (for further discussion, see Hanasaki et al. 2017).

The results of potential agricultural production of food and bioenergy are shown in Table 2. The production of food in the rainfed cropland is primarily influenced by the cropland area, but it is also affected by climatic change (see yield for food crop in the same table). The production of bioenergy crop was estimated at  $8800 \times 10^6$  t for Scenario S1 and  $12,300 \times 10^6$  t for Scenario S2. The estimated total bioenergy production goes along with the  $3.3 \text{ GtC year}^{-1}$  of BECCS or the primary assumption of this study. The relationship between bioenergy crop production and BECCS is expressed as follows (Eq. 5 of Kato and Yamagata 2014):

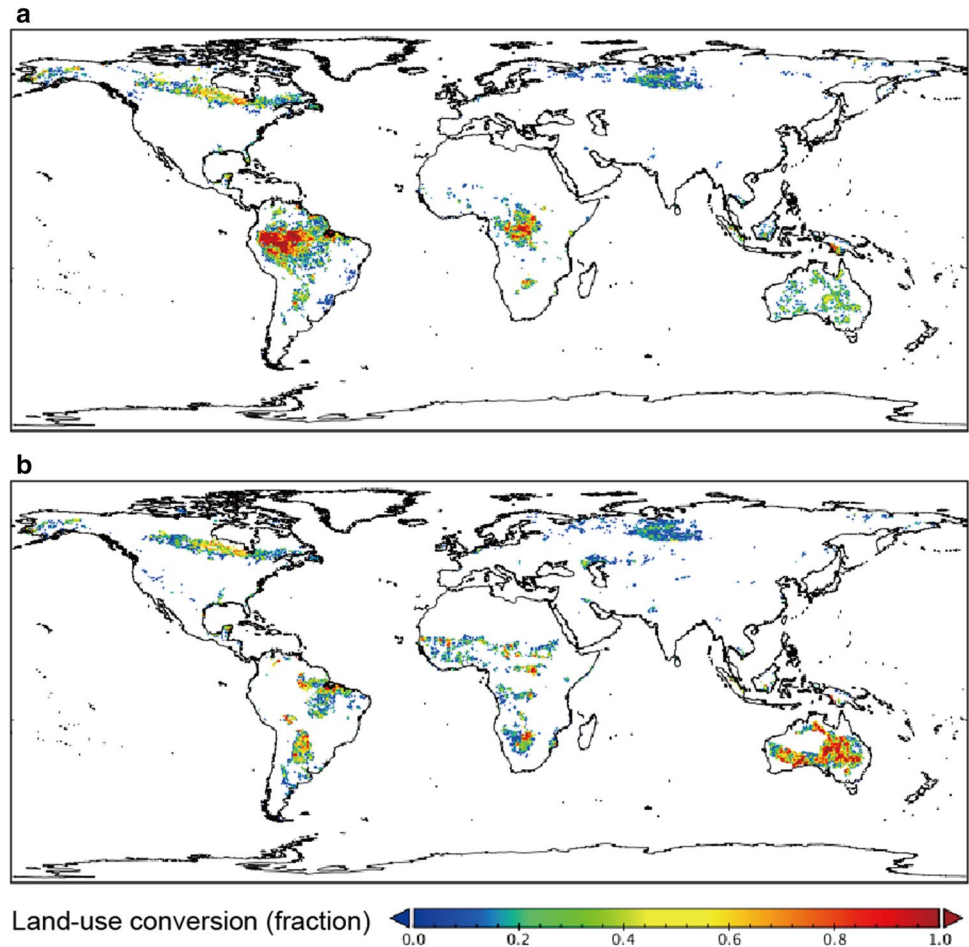
$$\text{PROD} = \text{BECCS} / (\text{CE} \times \text{CR}) \times 1 / f_{\text{cc}} \times 1 / f_{\text{biosng}},$$

where PROD is ligno-cellulosic crop production, BECCS is bioenergy carbon capture and storage, CE is the CCS capture efficiency, CR is the captured ratio of carbon to the carbon content in the unit of produced biofuel that depends on the scenario of CO<sub>2</sub> capture applications,  $f_{\text{biosng}}$  is the fraction of carbon in  $f_{\text{BioSNG}}$  to the carbon in biomass, and  $f_{\text{cc}}$  is the

carbon content of dry matter. Here we assumed  $\text{CE} = 0.90$ ,  $\text{CR} = 2.0$  or CO<sub>2</sub> is perfectly captured in the process of gasification and post combustion processes [see Scenario 2c of Kato and Yamagata (2014) for further detail],  $f_{\text{biosng}} = 0.4$ ,  $f_{\text{cc}} = 0.4545$  following Kato and Yamagata (2014). Using this relationship, bioenergy crop production of 8800 and  $12,300 \times 10^6 \text{ t year}^{-1}$  is equivalent to 2.88 and  $4.03 \text{ GtC year}^{-1}$  of BECCS, which is consistent with the  $3.3 \text{ GtC year}^{-1}$  of the target.

The global average yield of bioenergy crop was 35.2 and  $24.6 \text{ t ha}^{-1}$ , respectively, indicating that irrigation increased the yield by approximately 50% (i.e., required land use became 2/3). The effect of irrigation, or the fractional change in crop yield due to application of irrigation is shown in Fig. 6. The effect is prominent in arid and semi-arid regions in western North America, the Mediterranean, southern Africa, Central Asia, western South Asia, and eastern Australia. The abundant irrigation boosted the crop yield in these regions, because limitation in precipitation is the key restricting factor of the crop growth. However, available water from the river is quite limited in these regions, which pushed up the fraction of non-river-originated water

**Fig. 4** Areal fraction of bio-crop farmland in 2099 transferred from forest (S3) [land fraction]. **a** No reserved land (S3-1) and **b** with reserved lands for biodiversity hotspots (S3-2)



**Table 1** Land and irrigation required for bioenergy production

	Base (circa 2000)	Scenario S1 (2090s)	Scenario S2 (2090s)
Land (M ha)			
Food			
Irrigated	270	270	270
Rainfed	1300	1600	1350
Bioenergy			
Irrigated	0	250	0
Rainfed	0	0	500
Irrigation (km <sup>3</sup> year <sup>-1</sup> )			
Food	1420	1580	1480
Bioenergy	0	1910	0
Total	1420	3490	1480
From river	760	1580	760
From other sources	660	1910	720

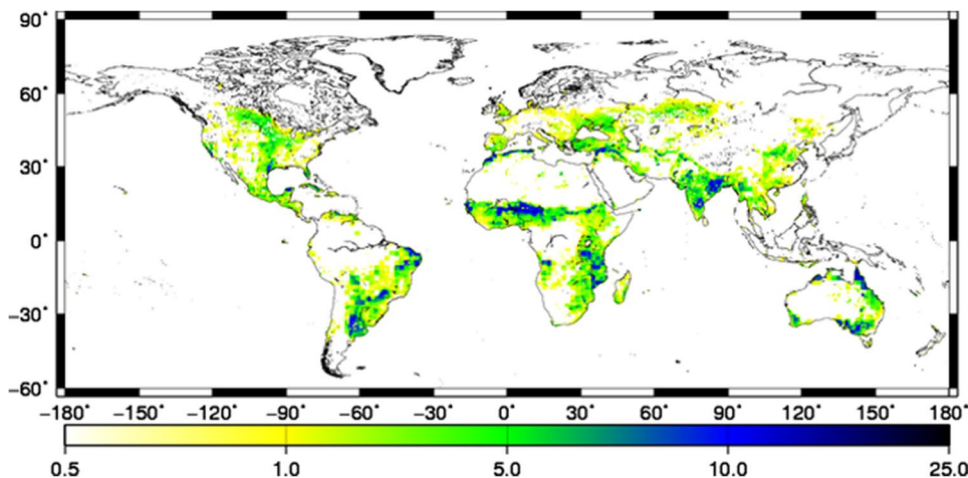
resources of Scenario S1. Moreover, vast irrigated food cropland area is concentrated in these regions as of today. Further enhancement of irrigation for growing bioenergy crop would likely conflict with food production. This is

particularly a concern, because climate models are projecting a large decrease of food crop yield due to the climatic change even during this century.

### Ecosystem model

Under the S3-1 (no reserved land) and S3-2 (with reserved land) scenarios, a vast area of natural ecosystems is converted to bioenergy crop cultivation. In our simulation, global NPP increased from 56.5 Gt C year<sup>-1</sup> in the 1990s to 65.6 Gt C year<sup>-1</sup> in the 2090s, mainly because of the effects of CO<sub>2</sub> fertilization. Because crops have high productivity comparable with those in forests, the prescribed land-use conversion did not largely affect global total NPP. As shown in Fig. 7a, global NPP increased almost linearly until around 2060 when it peaked; such trend is in parallel with atmospheric CO<sub>2</sub> concentrations. In each case, terrestrial ecosystems acted as a small net sink of CO<sub>2</sub> including emissions from land-use change and biomass burning, with a considerable range of interannual variability due to climate conditions (Fig. 7b). Note that this net CO<sub>2</sub> sink is only by ecosystem carbon stock, and sequestration by CCS should be evaluated separately. Carbon stocks in vegetation biomass

**Fig. 5** Irrigation water requirement for bioenergy crops under Scenario S1 in the 2090s ( $m^3 s^{-1}$ )

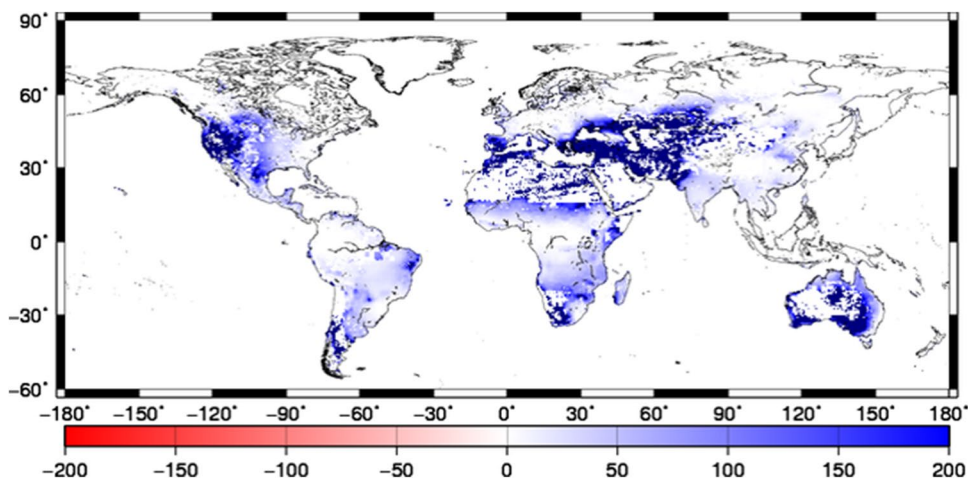


**Table 2** Production of bioenergy and food crop

	Base (circa 2000)	Scenario S1 (2090s)	Scenario S2 (2090s)
<b>Production (M t)</b>			
<b>Food</b>			
Irrigated	1570	1480	1480
Rainfed	5930	6670	5630
<b>Bioenergy</b>			
Irrigated	0	8800	0
Rainfed	0	0	12,300
<b>Yield (<math>t ha^{-1}</math>)</b>			
<b>Food</b>			
Irrigated	5.8	5.4	5.4
Rainfed	4.5	4.2	4.2
<b>Bioenergy</b>			
Irrigated	–	35.2	–
Rainfed	–	–	24.6

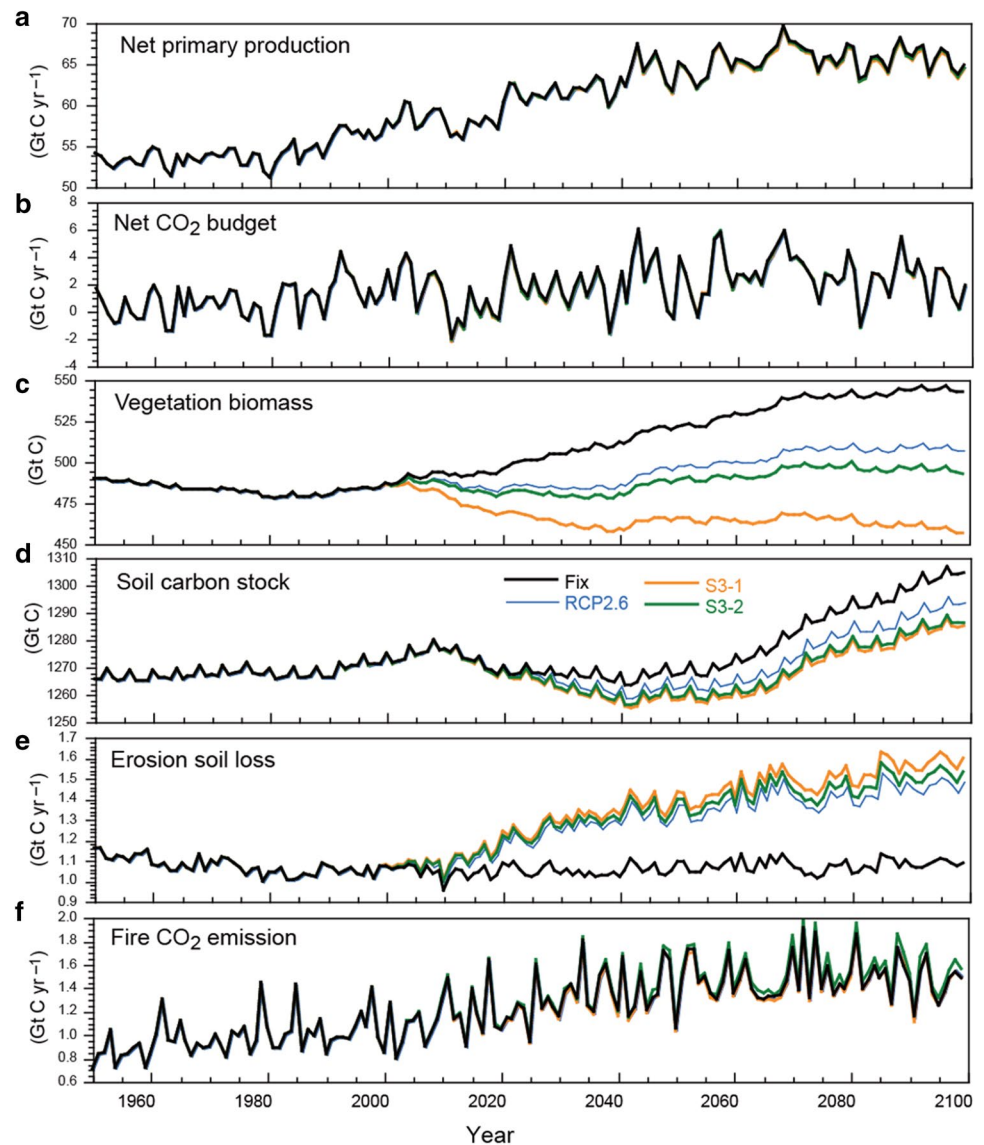
(Fig. 7c) and soil organic carbon (Fig. 7d) showed, in our simulation, clear difference among scenarios with a small range of decadal variability. With no land-use change after 2000, vegetation biomass increased from 483 Gt C in the 1990s to 544 Gt C in the 2090s. Under the S3-1 scenario, it decreased to 460 Gt C due to deforestation in tropical forests. In contrast, under the S3-2 scenario, vegetation biomass increased slightly (495 Gt C in the 2090s, a bit lower than 509 Gt C of the RCP2.6-based case), indicating the effectiveness of reservation for biodiversity hotspots. Soil carbon stock decreased in the land-use cases to some extent in the early twenty-first century and then increased gradually due to accumulation in temperate and boreal ecosystems. Here, the difference between the results of S3-1 and S3-2 was not so large, because soil carbon stock in tropical rainforests is low and comparable with rangelands. The average rate of net carbon sequestration under S3-2 scenario (about  $0.3 Gt C year^{-1}$ ) is comparable with the present level of terrestrial uptake or climate regulation services including

**Fig. 6** The effect of irrigation on yield of bioenergy crop or the percentage change of the yield between irrigated and rainfed bioenergy crop in the 2090s (%)





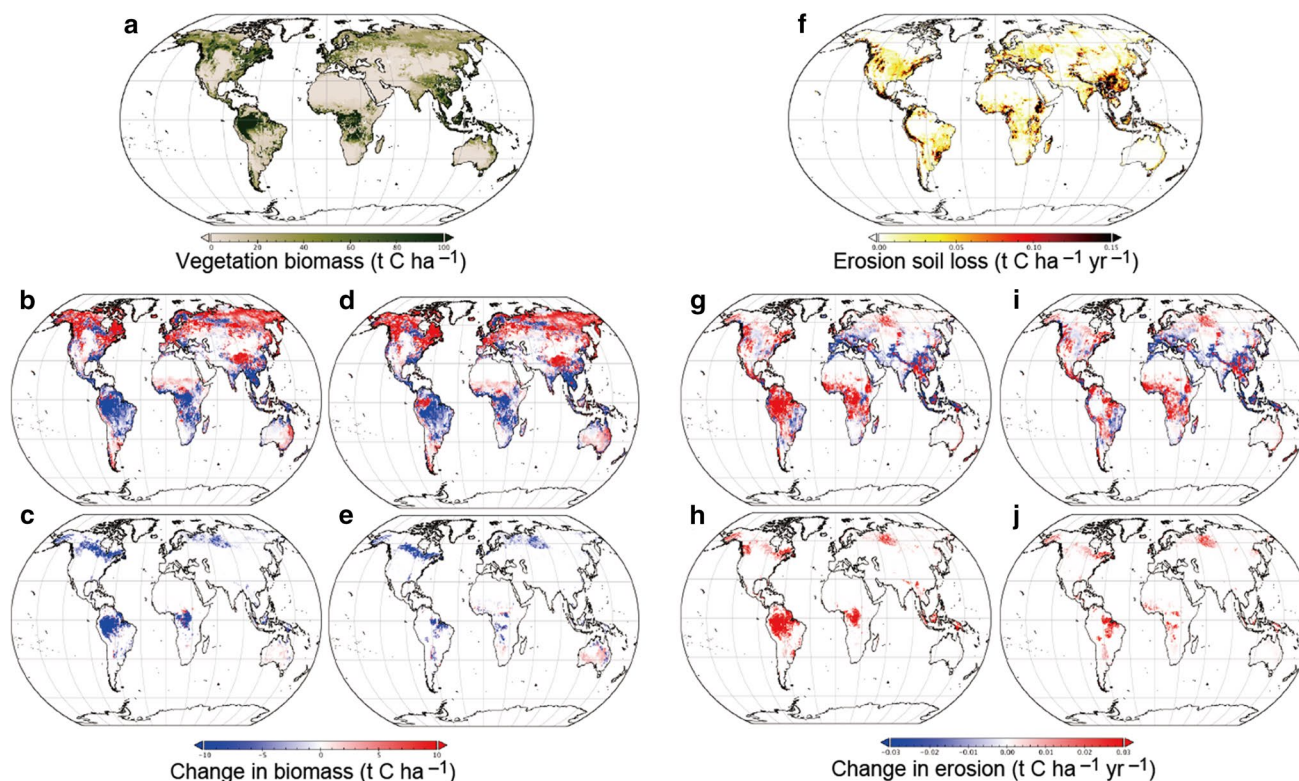
**Fig. 7** Time-series of simulated terrestrial properties related to ecosystem services using the S3 scenarios. **a** Net primary production, **b** net ecosystem CO<sub>2</sub> exchange, **c** vegetation biomass, **d** soil carbon stock, **e** soil loss from erosion, and **f** CO<sub>2</sub> emissions from biomass burning. Thick black line shows the result for fixed land-use case, thin blue for RCP2.6-based land-use case, thick orange for S3-1 (no reserved land) case, and thick green for S3-2 (with reserved land) case



the effect of land-use change (Le Quéré et al. 2016). Interestingly, our simulations for land-use cases (RCP2.6, S3-1, and S3-2) shows that soil loss by water erosion would be increasing during the twenty-first century, in contrast with the constant to weak decreasing trends during the twenty-first century of the fixed land-use case. Because soils provide fundamental support for many ecosystem services, such a loss of soil carbon could result in ecosystem degradation that could have adverse influences on the human society. On the other hand, biomass burning would increase until around 2040 probably due to the increase of fuel supplied from vegetation biomass production.

The terrestrial ecosystem functions are expected to change over the land surface. For example, vegetation biomass is expected to increase in the middle to high latitudes, because plants in these regions would enjoy favorable effects from higher atmospheric CO<sub>2</sub> concentrations and global

warming even under the RCP2.6-based climate. In contrast, under the S3-1 scenario, vegetation biomass in lower latitudes such as forests in Amazon Basin, Central Africa, and Southeast Asia is estimated to decrease largely during the twenty-first century (Fig. 8a–c), as a result of land-use conversion for bioenergy crop production. Because these tropical forests support important biodiversity and associated ecosystem services, such an intense biomass decrease should bring about adverse influence on local communities. Under the S3-2 scenario, biodiversity hotspots such as central Amazon were preserved. However, surrounding natural ecosystems were still seriously affected by land-use for bioenergy production (Fig. 8d–e). In Australia, expansion of bioenergy cultivation led to a slight increase of vegetation biomass, but it could not compensate for the massive loss in other forests. In our simulation, the loss of vegetation cover resulted also in deterioration of soil loss due to



**Fig. 8** Maps of simulated terrestrial properties related to ecosystem services and their change in the twenty-first century based on the S3 scenarios. **a** Vegetation biomass and **f** soil erosion loss in the 2090s, respectively. Difference between the 1990s and 2090s for **b** vegetation biomass under S3-1 (no reserve land), **d** vegetation biomass under

S3-2 (with reserve land), **g** soil erosion under S3-1, **i** soil erosion under S3-2, respectively. **c**, **e**, **h**, **j** Difference between the S3-based results in **b**, **d**, **g**, **i** and RCP2.6-based ones, showing the impact of BECCS deployment

water erosion. As shown in Fig. 8f, the present soil loss by water erosion occurs mainly in mountain areas, croplands, and monsoon Asia with high precipitation. Soils of tropical forests in the Amazon Basin and Central Africa are protected by dense vegetation cover, leading to lower soil loss due to water erosion than high precipitation. The intense land-cover change for bioenergy crop production in the tropics (S3-1) and subtropics (S3-2) could cause serious deterioration of soil loss (Fig. 8g–j) accompanied with degradation of vegetation productivity, hydrologic regulation, and biodiversity. Such soil loss also occurred in boreal regions, but with lower intensity.

### BECCS impact on land systems

By using state-of-the-art global land models and systematic land-use scenarios, a set of comprehensive simulations on the massive production of bioenergy was conducted. If approximately one-eighth of the cropland in 2090s was transferred into cropland for irrigated bioenergy, or in case of S1,  $8800 \times 10^6$  t of bioenergy crop together with 9% of increase in total food would be produced instead of 135% of additional water consumption. In case of S2,  $12,300 \times 10^6$

t would be produced instead of 5% of reduction in food production. From the view point of water resources, S1 is challenging, because it more than doubles the present water use. Water scarcity is observed in many parts of the world, and further increase in river water would exacerbate the problem. As shown in Table 1, the additional water would be abstracted from other sources than river water, which implies the need for intensive water resources development (dams, aqueducts, groundwater development). From the view point of food production, S2 is also challenging, because it decreases food production. The global average crop yield of food for S1 and S2 is approximately 7% smaller than the present level (notice that the  $\text{CO}_2$  fertilization effect and yield growth in the future are not taken into account in this study), indicating that a considerable improvement in efficiency is needed for food distribution to feed the world. From the view point of ecosystem services, S3 could be problematic with regard to ecosystem sustainability, because the extensive conversion of natural forests exerts undesirable impact on the ecosystem integrity, as it was the case where large-scale deforestations occurred in the tropical regions due to the rapid expansion of palm oil plantations. Moreover, loss of tropical forests in Amazon and Congo Basin would

bring about serious decline of biodiversity in these regions. Soil loss could be caused by exacerbated water erosion due to land-use conversion, if no strong deforestation regulation (such as REDD+) is implemented. Large-scale bioenergy crop deployment could also cause land degradations such as collapse of ecosystem structure and declined productivity.

It might be over-simplistic to assume that a vast extent of food cropland could be successfully transferred into bioenergy cropland in proportion to the total cropland area. It would likely be more realistic to assume an expansion of bioenergy cropland utilizing the scenarios developed by sophisticated land-use models. Complex trade-offs will occur among land (and ecosystem conservation), water, and food when a massive amount of bioenergy is produced. An integrated model that can deal with these interactions is urgently needed. For example, trade-offs between biodiversity conservation and land use become complicated when considering the existence of prioritized biodiversity hotspots (e.g., Myers et al. 2000; Newbold et al. 2016). Our knowledge on ecosystem functions and services are inadequate, such that forests can exert both positive and negative feedback effects on climate change depending on climatic conditions (Betts 2011). We need to deepen our understanding on specific land processes and their interactions.

## Conclusions and discussions

In this study, we demonstrated an integrated analysis on the impact of BECCS deployment on water, food, and ecosystems under three land-use S1-3 scenarios that correspond to RCP2.6.

In terms of food production, vast (approximately 25% in this study) conversion of cropland for bioenergy crop production may not be tolerable taking the population growth into account. Irrigation for bioenergy crop would enhance yield and reduce the area of cropland conversions. Although it could contribute to saving land for agricultural productions, this would double the water consumption due to irrigation globally. Since renewable riverine water has only limited room for expansion, additional huge irrigation could be sourced from non-renewable or non-local sources, which would exacerbate the global water scarcity risk.

On the other hand, in terms of sustainability of ecosystem services, unrestricted expansion of bioenergy crop cultivation at the expense of natural forests is not feasible, because it can cause serious extensive decline in carbon stock and related ecosystem services, although several regions receive some benefits. In this regard, we should pay more attention to the co-benefits of biodiversity conservation and climatic change mitigation activities for optimizing various sustainability benefits.

An important remaining issue for this kind of modeling is a more detailed consideration of socio-economic scenarios such as the shared socio-economic pathways (SSPs; see Riahi et al. 2017). SSPs, which are scenarios describing alternative future developments, consist of the sustainability (SSP1), middle of the road (SSP2), fragmentation (SSP3), inequality (SSP4), and fossil-fueled development (SSP5) scenarios. While we constrained land use assuming SSP2, different scenarios can lead to different conclusions. Besides, while SSPs and other socio-economic scenarios are typically country-level scenarios, regional/local-level socio-economic development is actually influential on water–food–ecosystems and land use in the regions. Use of spatially fine dataset on SSP1-5 would be an interesting next topic.

There are already several studies that have downscaled country-level socio-economic scenarios into spatially fine scenarios (e.g., Bengtsson et al. 2006; Grübler et al. 2007; van Vuuren et al. 2007; Gaffin et al. 2004; Hachadoorian et al. 2011; Nam and Reilly 2013; McKee et al. 2015; Yamagata et al. 2015; Jones and O'Neill 2016; Murakami and Yamagata 2016). Especially, as it could influence the future land use drastically, we need to study spatially explicit economic growth (GDP) impact on food preferences and food security and the trade-offs between water, food, and ecosystems. To support this kind of studies, we have also developed gridded GDP scenarios for SSP 1–3 (Murakami and Yamagata 2016) in addition to SSP2. Our newly developed socio-economic dataset will be used for the ISIMIP as one of the standardized input datasets. The datasets are downloadable from GCP website (<http://www.cger.nies.go.jp/gcp/population-and-gdp.html>).

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