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Global BECCS potential largely constrained by sustainable irrigation

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Abstract

Bioenergy with carbon capture and storage (BECCS) is crucial in many stringent climate scenarios. Although irrigation can enhance BECCS potential, where and to what extent it can enhance global BECCS potential are unknown when constrained by preventing additional water stress and suppressing withdrawal of nonrenewable water resources. With a spatially explicit representation of bioenergy crop plantations and water cycle in an internally consistent model framework, we identified the irrigable bioenergy cropland based on the water resources reserve. Irrigation of such cropland enhanced BECCS potential by only 5–6% (< 60–71% for unconstrained irrigation) above the rainfed potential (0.82–1.99 Gt C yr^{-1}) by the end of this century. Nonetheless, it limited additional water withdrawal (166–298 km^3 yr^{-1}), especially from nonrenewable water sources (16–20%), compared to unconstrained irrigation (1392–3929 km^3 yr^{-1} and 73–78%). Our findings highlight the importance of irrigation constraints in global BECCS potential.

To prevent dangerous anthropogenic interference with the climate system, the Paris Agreement set goals of limiting the global temperature increase to well below 2°C and pursuing efforts to limit it to 1.5°C[1]. To achieve such an ambitious temperature goal, removal of CO_2 and other greenhouse gases from the atmosphere (also known as negative emission) is considered inevitable[2-5]. Among the different negative emission technologies, large-scale deployment of bioenergy with carbon capture and storage (BECCS) has been considered one of the most promising methods in many stringent climate scenarios[3,6-8]. For example, a comprehensive review showed that a median BECCS deployment of around 3.3 Gt C yr^{-1} in 2100 is needed in scenarios consistent with the 2°C climate goal[3,9]. Large-scale BECCS deployment would require more land for bioenergy crop plantations. For example, a median range of 250–910 Mha of bioenergy cropland is needed across the different socioeconomic scenarios in representative concentration pathway (RCP) 2.6[10]. However, without adequate, careful management for environmental sustainability, bioenergy crop plantations on such a large spatial scale would lead to adverse effects, such as water scarcity, diminished biodiversity, land degradation, and desertification[2,9-19].

Reductions in the land area needed for bioenergy crop plantations could be achieved by enhancing biomass yields. Several studies have shown that irrigation can increase yields and thus reduce cropland area, but the global total irrigation water consumption would double or even triple[9,12,20-23] if water were limitlessly available at any location and time. Apparently, large-scale irrigation would further exacerbate the future water stress associated with the increasing demands of conventional water use (i.e., agricultural, industrial, and municipal water use)[14,24-29]. For instance, a recent study showed that irrigation would lead to severe water stress even exceed the impact from climate change itself when increasing bioenergy crops productivity to the level consistent with 1.5°C goal[30]. Without such prescribed external demand for productivity, where and to what extent irrigation can enhance the global BECCS potential remains unknown under sustainable water use, which we define as water use securing the local and downstream water availability for conventional water use and environmental flow requirements, suppressing nonrenewable water resources withdrawal, and preventing additional water stress. A previous study considered water availability at grid-cell level[22], but the downstream water availability, nonrenewable water resources use, and possible additional water stress were neither the focus nor included. Here, we addressed these knowledge gaps by incorporating the concept of sustainable water use as defined above into the irrigation management of bioenergy crop plantations. This enabled us to determine the global BECCS potential constrained by sustainable irrigation.

To prevent adverse effects pertaining to biodiversity, food production, land-use change emission, land degradation, and desertification due to large-scale land conversion, we adopted protections for the areas protected for biodiversity, areas of cropland, forest and wetland, and areas under land degradation and desertification. Under this perquisition, two land scenarios were developed for plantations of the dedicated second-generation bioenergy crops, namely *Miscanthus* and switchgrass. In the first scenario, pastureland is also protected (scenario PP). To consider the uncertainty of land-use conversion and dietary change (e.g., shifting toward less relying on livestock products[31]), we developed another scenario in which pastureland conversion (scenario PC) is allowed (see Fig. 1a and Methods for details). To reveal the irrigation water constraints for global bioenergy crop plantations, we investigated three distinct irrigation scenarios: no irrigation (rainfed; RF), irrigation of all bioenergy cropland without any water constraints (full irrigation; FI), and irrigation of some bioenergy cropland with constraints of water availability (sustainable irrigation; SI). In SI, we simulated the volume of water available for bioenergy crop irrigation as the reserve of the renewable water resources at the grid-cell level. Then, we assigned the irrigable bioenergy cropland within the availability of the reserved water based on the bioenergy crop water consumption (see Fig. 1b and Methods for details). Simulations were conducted with the global hydrological model H08, which includes anthropogenic water use and management (see Methods for details). H08 specifies the source of water globally at a spatial resolution of 0.5° at daily time steps. Water sources are divided into surface water (river, aqueduct, reservoir, desalinated seawater, and non-local and nonrenewable surface water) and groundwater (renewable groundwater and nonrenewable groundwater). The environmental flow required to safeguard river ecosystems is considered. For the six scenario combinations, simulations were conducted for 2080–2099 using H08 (see Methods for details). Based on a series of simulations, we identified the spatial distribution and extent of the irrigable bioenergy cropland from the total bioenergy cropland, quantified the gain of the global BECCS potential due to sustainable irrigation, specified the sources of the additional irrigation withdrawal, analyzed the water stress additionally imposed, and conducted the sensitivity analysis.

Results

Our results follow.

Global BECCS potential

Under the rainfed condition (RF), the average global BECCS potential in 2090 was only 0.82 and 1.99 Gt C yr^{-1} in the PP and PC scenarios, respectively (Fig. 2a). The BECCS potential reached 1.32 and 3.42 Gt C yr^{-1} (60% and 71% increases compared to that under RF) under full irrigation (FI) in PP and PC, respectively, whereas under sustainable irrigation (SI), the BECCS potential was 0.88 and 2.09 Gt C yr^{-1} in PP and PC, respectively (5% and 6% increases compared to that under RF). This indicates that the gain in the BECSS potential is largely constrained if implementing sustainable irrigation management as we defined in SI. Note that the carbon capture rate and conversion efficiency are important parameters and have a large impact on the BECCS potential[12,32]. For instance, with lower capture ratios, the BECCS potential could be reduced to 50% or 75% of current estimates (Supplementary Fig. 1). Therefore, our estimates appear optimistic because the calculation was based on the assumption of converting the biomass into synthetic natural gas with a higher capture rate (see Methods).

Global bioenergy plantation land and irrigated area

In total, 188 and 444 Mha were assigned to bioenergy crop plantations in the PP and PC scenarios, respectively (Fig. 2b). Although the land area under PP is smaller than that under PC, it is beneficial for reducing greenhouse gas emissions induced by land-use change from pastureland[33]. The respective areas irrigated under RF, SI, and FI with the different irrigation scenarios, were 0, 39, and 188 Mha in PP and 0, 64, and 444 in PC, respectively. The ratio of irrigated land to total bioenergy plantation land under SI was small (21% and 14% in PP and PC, respectively). Spatially, the land available for bioenergy crop plantations was mainly distributed in Russia, South America, middle Africa, and parts of southeast Asia and the United States (Supplementary Fig. 2a and 2b), whereas the irrigated areas under SI were mainly concentrated in high-latitude areas in Russia and central Africa (Supplementary Fig. 3a and 3b).

Global additional irrigation water withdrawal

Sustainable irrigation resulted in little volume of additional water withdrawal (166–298 km^3 yr^{-1}) (Fig. 2c), corresponding to only 6–11% of the current agricultural water withdrawal (2769 km^3 in 2010)[34]. From the perspective of water sources, water was taken mainly from renewable sources under SI. The largest water source was rivers (73–76%), followed by renewable groundwater (5–6%). Only 16–20% of the water was sourced from non-sustainable water sources[35] (non-local and nonrenewable surface water and nonrenewable groundwater). By contrast, under full irrigation, a large volume of irrigation water withdrawal (1392–3929 km^3 yr^{-1}) was additionally needed, and the lower and higher bounds of this range were comparable to the sum of current industrial and municipal water withdrawal (1232 km^3 in 2010)[34] and the present total water withdrawal for all sectors (4001 km^3 in 2010)[34], respectively. Moreover, water was taken mainly from non-sustainable water sources (73–78%) because streamflow or renewable groundwater is unavailable for most locations in arid or semiarid zones when it is needed in the daily interval simulation. Water taken from rivers accounted for only 16–19% and that from renewable groundwater accounted for only 4%. This indicates that sustainable irrigation largely reduces the total amount of water withdrawal and the fraction of non-sustainable water withdrawal.

Note that the additional water withdrawal under sustainable irrigation was accompanied by very low additional water stress (Fig. 3a and Supplementary Fig. 4a; Supplementary Table 1 details the water stress categories), whereas it was accompanied by significant additional water stress under full irrigation in many regions, such as the Southeastern South America, Southern Africa, North-East Brazil, East Africa, North Asia, West Africa, Central North America, Central Europe, West Asia, Central America, Central Asia, and East Asia especially in the land Scenario PC (Fig. 3b and Supplementary Fig. 4b, see Supplementary Fig. 5 for region details).

Sensitivity analysis

Theoretically, our simulation of SI was sensitive to two parameters: the water use fraction (WUF; set at 10% under SI) and the reference flow (REF; set at Q95 under SI). Here, WUF is the fraction of the available water used for bioenergy crop irrigation and REF is the streamflow rate to define the local available water resources; see Methods for parameter details). Parameter combinations can enhance the BECCS potential via intensified irrigation (Fig. 4a–4c), but there is a tradeoff between additional irrigation water withdrawal and the corresponding BECCS potential. For instance, in land scenario PP, if we set WUF=50% or 90%, and fix REF=Q95, the average irrigation water withdrawal and the non-sustainable water withdrawal would increase to 2.2 or 2.8 times, and 5.3 or 8.4 times of the original values (when WUF=10% and REF=Q95), respectively (Fig. 4d–4i). The findings were similar in land scenario PC. This indicates that increasing WUF allows more irrigation water withdrawal for bioenergy crops, but it eventually results in increased use of non-renewable and non-local water resources. However, the increase in the corresponding BECCS potential was quite limited at 7% (from 0.88 to 0.94 Gt C yr^{-1}) or 10% (from 0.88 to 0.97 Gt C yr^{-1}) (Fig. 4j–4i) because most of the increased irrigated area is concentrated in Russia and the central Africa (Supplementary Fig. 3), where the biomass yield is relatively high, even under rainfed condition, and irrigation has limited effects on the biomass yield. In comparison, in land scenario PP, if we fix WUF=10%, but set REF=Q10, the average irrigation water withdrawal and the non-sustainable water withdrawal would increase to 3.0 times and 9.6 times the original values (when WUF=10% and REF=Q95), respectively (Fig. 4d and 4g). Similarly, the increase in the average BECCS potential would be quite limited at 11% (Fig. 4j). Our sensitivity test indicated that the BECCS potential could not reach the level under full irrigation even with the setting for the maximum water use (e.g., when WUF=90% and REF=Q10), because the irrigable area is constrained by the available water in the arid regions, especially in the PC scenario. Moreover, for the 10%, 50%, and 90% water use fractions, our results indicated that there are apparently nonlinear relationships between the reference flow and the irrigated area, irrigation water withdrawal, and the non-sustainable irrigation withdrawal, with an inflection point at REF of Q50, above which the volumes of these three terms increase sharply (Fig. 4a–4l). Note that the ranges shown in the shaded area represent the uncertainty, mainly due to the biomass source of

Miscanthus or switchgrass. For example, the higher bound of the range of the BECCS potential is based on *Miscanthus*, while the lower bound is based on switchgrass (Supplementary Figs. 6 and 7).

Implications and caveats

With increasing concerns about, and continuing discussion of, the feasibility and adverse effects of large-scale BECCS deployment, investigating the BECCS potential by considering sustainability constraints of water and land is critical[2,11,12,16,36-39]. Our study proposes a sustainable irrigation method for bioenergy crop plantations that does not impose additional water stress, adding insight to the continuing discussion of the future of BECCS. Our simulation of only 0.88 Gt C yr^{-1} under PP_SI can be regarded as the maximum BECCS potential with strict consideration of water and land sustainability that would not lead to additional water stress, biodiversity loss, or competition with food production. This relatively low volume of BECCS potential implies that climate mitigation scenarios that rely mainly on BECCS deployment may have difficulty or present risk in achieving the 2°C or 1.5°C climate goal[3,40] (e.g., the median BECCS demand varied from 1.6 to 4.1 Gt C yr^{-1} in scenarios that consistent with the 2°C or 1.5°C goal in 2100[41]). This result is consistent with the opinion that BECCS might not be considered the dominant technology in IPCC and other scenarios aiming at the Paris climate goal[42]. Our specification of the amounts and sources of additional irrigation water withdrawal for bioenergy crop plantations among the different irrigation scenarios elucidates the BECCS potential and irrigation water tradeoffs, especially for distinguishing the sustainable and non-sustainable water sources, which are typically ignored in previous studies based on integrated assessment models, although they have more explicit economic frameworks[39,43]. This also complements the studies[20,22] based on similar biophysically constrained models, because such source-specific water withdrawal has not yet been reported.

Although we quantified the constraints of sustainable irrigation on the global BECCS potential, continued research is needed. First, involvement of field water management measures (e.g., mulching, water collection, and conservative tillage) as adopted in a previous study[22] in the sustainable irrigation scheme can provide valuable complementary insights into the tradeoffs between BECCS potential and additional water withdrawal. For example, there might be a considerable reduction of the additional water withdrawal due to the decrease of crop evapotranspiration or irrigation target although such measures might be hampered due to the large economic investments[22]. Second, detailed combination of the sustainable irrigation scheme with a temporal evolution of the land use scenario that systematically considers the peak warming level, peak warming time, and post-peak temperature change[36] can further illustrate the nexus of water, BECCS potential, and the climate goal in a temporally specific manner. Third, the bioenergy plantation land described here excludes current cropland, which means additional irrigation equipment would be needed; therefore, an explicit consideration of the cost and feasibility of the additional infrastructure implementation for bioenergy crop irrigation would provide a better understanding of the feasible BECCS potential. Finally, we acknowledge that the BECCS potential could be increased with an optimized plantation scheme that also includes woody biomass, although its yield is generally lower, and the harvest interval is much longer than for the herbaceous biomass considered here[44]. Similarly, including the feedstocks from the managed forest and agricultural residues could also increase the BECCS potential[45,46].

Overall, our findings help to reveal the constraints of sustainable water management on irrigable area for bioenergy crop plantations and therefore the final global BECCS potential.

Our study highlights the importance of determining the biophysically constrained BECCS potential when pursing the 2°C or 1.5°C climate goal.

Methods

To quantify the water availability constraints on the global BECCS potential explicitly, in this study, we used the global hydrological model H08, which allows the simultaneous simulation of the bioenergy crop growth, yields, and corresponding irrigation water withdrawal and sources within a detailed spatiotemporal representation of the global hydrological cycle with major anthropogenic activities. With strict protections for natural protected areas, forest, cropland, pastureland, wetland, etc., we developed two land scenarios for bioenergy crop plantations, treating one as a comparison to consider the land uncertainty. For each land scenario, we considered three distinct irrigation scenarios (no irrigation, full irrigation, and sustainable irrigation). Finally, we estimated the average global BECCS potential and additional irrigation water withdrawal of the two bioenergy crops under each scenario for 2080–2099, with explicit consideration of climate and socioeconomic changes. The model, scenario, simulation, and method used to calculate the BECCS potential are described in detail in the following sections.

Global hydrological model H08

H08 is a grid-cell-based global hydrological model that has the function of addressing the impacts of major human activities, such as irrigation and reservoir operation, on the global hydrological cycle. It has six sub-models, including land surface hydrology, river routing, reservoir operation, crop growth, environmental flow, and anthropogenic water withdrawal[47,48]. It was updated by the inclusion of groundwater recharge and abstraction, aqueduct water transfer, local reservoir, seawater desalination, and return flow and delivery loss schemes[35].

These sub-models and schemes enable H08 to simulate natural and anthropogenic hydrological processes and crop growth, at a spatial resolution of 0.5° and a daily interval.

Specifically, the land surface hydrology sub-model is a standard land surface model that solves the surface water and energy balance and simulate the main water cycle components, such as evapotranspiration and runoff. Streamflow is simulated by the river routing through the global digital river network. The simulation explicitly includes the flow regulation of 963 major world reservoirs. The crop growth sub-model is based on heat unit theory to accumulate the biomass and can simulate the cropping duration and crop yields for 18 traditional crops and 2 bioenergy crops (*Miscanthus* and switchgrass). Factors such as water and air temperature are regulated to constrain the biomass production. The simulated bioenergy crop yields for *Miscanthus* and switchgrass have been calibrated and validated through site-specific data globally, which agreed well with the observations[49]. The simulated yield of *Miscanthus* was generally higher than that of switchgrass (Supplementary Figs. 8 and 9), e.g., with respective mean values of 19.2 and 7.6 Mg ha^{-1} yr^{-1} under PP (pastureland protection)_RF (rainfed), because *Miscanthus* has a higher radiation use efficiency and a longer cropping period. Sustainable irrigation increased the yield marginally, e.g., the yield was increased by 15% and 16% under PP_SI compared to 50% and 48% under PP_FI for *Miscanthus* and switchgrass, respectively. A complete description of the model and its performance, including information on the bioenergy crop water consumption, water use efficiency, and the irrigation effect among different climate zones can be found in Ai et al.[49]. The environmental flow sub-model can estimate the streamflow that is needed to maintain the aquatic ecosystem. The anthropogenic water withdrawal sub-model can simulate the water requirements for irrigation (for both food and bioenergy), industry, and municipalities, which are allocated to seven sources (rivers, aqueducts, local reservoirs, seawater, non-local and nonrenewable surface water, renewable groundwater, and nonrenewable groundwater)[48]. Irrigation water demand is simulated by the difference in the soil moisture deficit (i.e., the discrepancy between the targeted and actual soil moisture) during crop- and site-specific cropping periods. The estimated major hydrological components (streamflow and total water withdrawal) have been validated in a series of previous studies[35,47,48]. The simulated irrigation water demand by *Miscanthus* is generally higher than that by switchgrass (Supplementary Fig. 10), varying from less than 200 mm yr^{-1} to over 1000 mm yr^{-1} depending on the spatial variation in precipitation and crop water consumption.

Water withdrawal in H08. In H08, water withdrawal is designed to meet the water use of the municipal, industrial, and irrigation sectors. To meet the entire water requirements, water is abstracted from both surface water and groundwater. Note that water is first abstracted to meet municipal use, then industrial use, and finally irrigation water use. The order of water abstraction from each source of surface water and groundwater follows. For surface water, water is first taken from river until it meets the requirements, or the streamflow reaches the environmental flow requirements. If streamflow cannot meet the requirements, water is taken from an aqueduct, local reservoir, seawater (assumed for municipal and industrial uses only) and the so-called non-local and nonrenewable surface water. For groundwater, water is first taken from renewable groundwater and then from nonrenewable groundwater. A schematic figure is shown in Supplementary Fig. 11. Additional details are provided in Hanasaki[39].

Environmental flow requirements in H08. Environmental flow is the flow needed to maintain the river ecosystem. H08 uses Shirakawa's model[50] to estimate environmental flow. The mechanism is as follows: first, the land area is divided into the four climate categories of dry, wet, stable, and variable based on the monthly streamflow (q); then, the environmental flow requirements are calculated using different equations under each climate and specific condition (Supplementary Table 2).

Land and irrigation scenarios

In the standard H08, one grid cell is separated into the four sub-cells (four mosaic land uses) for double-irrigated cropland, single-irrigated cropland, rainfed cropland, and other land uses[51]. Here, we added the two land uses for irrigated bioenergy crops and rainfed bioenergy crops in each grid cell with explicit consideration of two bioenergy land scenarios and three irrigation scenarios. This enabled us to estimate soil moisture and other hydrological fluxes specific to bioenergy crops.

Two bioenergy land scenarios were developed (Fig. 1a). First, similar to a previous study[22], a whole grid cell was excluded from conversion to bioenergy land if it was in the World Database for Protected Areas (WDPA)[52], a biodiversity sensitive and land degraded area[53], or a wetland[54]. An entire grid was also excluded from conversion to bioenergy if the yield was less than or equal to 2 Mg ha^{-1} yr^{-1} or if it was covered by a desert climate. Then, the land use fractions for cropland[51], pastureland[55], forest (both managed and unmanaged)[55], and built areas[55] in each grid cell were excluded from conversion to bioenergy land under the pastureland protection (PP) scenario. By contrast, pastureland[55] was not excluded under the pastureland conversion (PC) scenario to investigate the land uncertainty. Finally, the land fraction remaining in each grid cell refers to the fraction of the total bioenergy land. Here, the fraction of pastureland, forest, and built areas in each grid cell in 2090 under RCP 2.6 and SSP1 (sustainability), SSP2 (middle of the road), and SSP5 (fossil-fuel development) that are compatible with the 2°C climate goal are from AIM/Hub[56] and AIM/PLUM[57] outputs[55]. The global areas for each land use are shown in Supplementary Fig. 12. To maintain the current cropland area, the fraction of cropland used here is from the default setting in H08, because the cropland areas from the AIM/Hub and AIM/PLUM outputs are lower than those in H08 (Supplementary Fig. 12).

After determining the fraction of total bioenergy land in each grid cell, as shown in Fig. 1b, we partitioned it into the fractions of irrigated and rainfed bioenergy land. In total, we considered three distinct irrigation scenarios (no irrigation, full irrigation, and sustainable irrigation). For sustainable irrigation (SI), the available water rate used for irrigating the bioenergy crop was estimated as the product of reference flow (REF) and water use fraction (WUF). Here, the reference flow (kg s^{-1}) is the flow rate used to estimate the local water availability and is expressed as the different percentiles of the mean monthly streamflow (2080–2099) (e.g., Q95 is the 95th percentile flow, while Q10 is the 10th percentile flow). This was then aggregated to annual values as the annual amount of the available irrigation water (kg yr^{-1}) for bioenergy crops. To calculate a given percentile flow (P^{th}, e.g., P is 95 for 95th percentile flow), the mean monthly flow was firstly arranged in a descending order. Then, the P^{th} percentile flow was obtained by taking the value from the ordered list that corresponds to the rank (calculated as $\left\lfloor \frac{P}{100} \times 12 \right\rfloor$). In this sense, Q95 indicates a low flow rate, while Q10 indicates a high flow rate. That is, the amount of available irrigation water in a grid cell increases with the change in reference flow from Q95 to Q10. The water use fraction is the ratio of irrigation water withdrawal to the reference flow. These two parameters were set as Q95 and 10%, respectively. This ensures that the remaining 90% of the low flow can be used for downstream water use (i.e., agricultural, industrial, and municipal water withdrawal), especially in dry periods. To evaluate the variability of the two parameters, a sensitivity test was conducted by replacing the 10% water use fraction with 50% and 90%, as well as by replacing the Q95 flow with other Q values (Q90, Q80, Q70, Q60, Q50, Q40, Q30, Q20, and Q10). Then, the irrigated bioenergy area could be obtained by dividing the annual amount of available irrigation water (kg yr^{-1}) by the annual water consumption per area (kg m^{-2} yr^{-1}) for each bioenergy crop (*Miscanthus* and switchgrass). The fraction of irrigated bioenergy land was then calculated as the irrigated bioenergy area divided by the total land area in each grid cell. Finally, the fraction of rainfed bioenergy land was obtained by calculating the difference between the fractions of total and irrigated bioenergy land in each grid cell. For rainfed (RF), the bioenergy crop in a grid cell was all rainfed with no irrigated fraction. For full irrigation (FI), the bioenergy crop in a grid cell was all irrigated with no rainfed fraction.

Simulations

A series of simulations was conducted with H08 for different purposes. First, the crop submodel was used to obtain the annual yield and water consumption per area for each bioenergy crop, which were used in the process of making the bioenergy land mosaic. Second, the coupled model of H08 (without bioenergy) was used to obtain monthly discharge, which was used to calculate the reference flow. Third, the coupled model of H08 (with bioenergy) was used to obtain the main outputs, such as bioenergy crop yield and irrigation water withdrawal for each combined irrigation and land management scenario. Additional water withdrawal for bioenergy crops under full and sustainable irrigation conditions was determined by calculating the difference compared to that under the rainfed condition. Note that environmental flow was considered in each coupled model simulation. Future projections[24] of water demand for domestic use and industry were used in each coupled simulation. With the goal of the 2°C climate target, we used ISIMIP2b[58] data generated using the outputs from four bias-corrected general circulation models (GCMs): GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 under RCP2.6. Here, daily gridded data (0.5°) for air temperature, wind speed, air pressure, specific humidity, rainfall, snowfall, and downward shortwave and longwave radiation for the period 2075–2099 were used as the climate forcing to H08. The simulations for the period 2080–2099 were used for the analyses, and the first 5 years (2075–2079) were used as spin-up.

BECCS potential calculation

Here, BECCS potential was estimated as follows[9,32]:

$$\text{BECCS potential} = Production \times CE \times CR \times f_{cc} \times f_{biosng}$$

where *Production* is the bioenergy crop production obtained as the product of the bioenergy crop yield and the bioenergy land area, *CE* is the CCS capture efficiency, *CR* is the ratio of captured carbon to the carbon content per unit of produced biofuel, which depends on the scenario of the CO_2 capture application, f_{cc} is the carbon content of dry matter, and f_{biosng} is the fraction of carbon in synthetic natural gas to the carbon in biomass. Here, *CE* was set as 0.9, *CR* was set as 2.0, f_{cc} was set as 0.4545, and f_{biosng} was set as 0.4 for the two bioenergy crops, as used in previous studies[9,32].

Data availability

The AIM/Hub and AIM/PLUM outputs are available from the website: https://www-iam.nies.go.jp/aim/data_tools/aimssp/aimssp.html. The input meteorological data are available at: http: //h08.nies.go.jp. All datasets used in this study are also available from the corresponding author on reasonable request.

Code availability

The code and technical information about the H08 model are available at: http: //h08.nies.go.jp. The code used for the simulation is also available from the corresponding author on reasonable request.

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Author contributions

N.H. and Z.A. conceived the research and designed the scenarios; Z.A. developed the code, conducted the simulation, analyzed the data, and prepared the manuscript; T.H. and S.F. contributed to the scenario design, N.H., V.H., T.H., and S.F. edited and improved the manuscript.

Competing interests

The authors declare that they have no competing interests.

Figure captions

Fig. 1 Schematic figures showing the process used to develop the two land scenarios (a) and the three distinct irrigation scenarios (b) for bioenergy crop plantations.

Fig. 2 The global BECCS potential (a) and corresponding bioenergy land area (b) and additional irrigation water withdrawal (c) under each combined scenario in 2090 (average of 2080–2099). PP and PC denote the two land scenarios of pastureland protection and pastureland conversion, respectively. SI, FI, and RF denote the three irrigation scenarios of sustainable irrigation, full irrigation, and rainfed, respectively. NNS denotes non-local and nonrenewable surface water. The three red lines in the panel (c) show the industrial and municipal water withdrawal, agricultural water withdrawal, and total water withdrawal in 2010 according to the FAO, respectively.

Fig. 3 Additional water stress due to additional irrigation water withdrawal for bioenergy crop plantations under PP (pastureland protection)_SI (sustainable irrigation) (a) and PP (pastureland protection)_FI (full irrigation) (b).

Fig. 4 Sensitivity tests for irrigated area (a–c), additional irrigation water withdrawal (d–f), non-sustainable water withdrawal (g–i), and the BECCS potential (j–l) with different water use fractions (10%, 50%, and 90%) and reference flows (Q95, Q90, Q80, Q70, Q60, Q50, Q40, Q30, Q20, and Q10). The solid and dashed lines are the mean values under PP (pastureland protection) and PC (pastureland conversion), respectively, and the shaded area shows the minimum to maximum ranges across the scenarios and bioenergy crop types.

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