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Contributions of countries without a carbon neutrality target to limit global warming

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Bioenergy with carbon capture and storage (BECCS) is a key negative emission technology for climate mitigation. Some countries have made no commitment to carbon neutrality but are viewed as potential BECCS candidates (hereafter, non-CN countries). Here we analyze contributions of these countries to global climate mitigation with respect to BECCS using an Earth system model with explicit representations of bioenergy crops. Switchgrass cultivation in these non-CN countries can further remove atmospheric CO_2 by 9.1 ± 2.8 and 19.9 ± 5.2 PgC in the low-warming and overshot scenarios, resulting in an extra biogeochemical cooling effect of 0.01 ± 0.04 to 0.02 ± 0.06 °C. This cooling is largely counterbalanced by the biophysical warming, but the net effect is still an extra cooling. The non-CN countries play a more important role in the low-warming scenario than in the overshoot scenario, despite the inequality of temperature change among countries. Our study highlights the importance of a global system for climate mitigation.

Bioenergy with carbon capture and storage (BECCS) has been widely used by integrated assessment models (IAMs) in future climate mitigation scenarios[1,2]. It is projected to remove 150 ~ 1200 $GtCO_2$ from the atmosphere by 2100 for limiting warming to 1.5 °C[3]. The net carbon-dioxide removal (CDR) capacity of BECCS is mainly determined by bioenergy crop yields[4], cultivation area[5], the CCS efficiency, and land-use change (LUC) carbon emissions[6–9]. The CDR potential of BECCS also varies with energy production methods and regional characteristics, while its deployment depends on economic and policy contexts, requiring substantial investments and strategic frameworks to meet climate targets[10,11]. Additionally, global responsibility for CDR is unevenly distributed, with varying capacities and obligations among countries[12]. In addition to the biogeochemical cooling from the reduced CO_2 concentration[13], large-scale cultivation of bioenergy crops alters the land surface properties (e.g., albedo, evapotranspiration), leading to biophysical temperature changes[14]. Both CDR and the biophysical effects of bioenergy cultivation show strong spatial variations[13,14]. In particular, bioenergy cultivation in one region can affect the climate of others by causing changes in atmospheric circulation. However, unlike IAMs assuming a global coordinated mitigation starting this decade, currently, only 130 countries have set a target of achieving net zero or carbon neutrality (CN, hereafter, CN countries, Fig. 1), despite of varying degrees of progress (Supplementary Fig. 1, Methods). There are still 61 countries without a CN target (non-CN countries) by November 2021, altogether representing about 11% of global anthropogenic CO_2 emissions[15]. It remains unclear to what extent CDR and temperature change would be lost if non-CN countries do not implement BECCS while CN countries do. Addressing this question could bolster climate negotiations on whether to incentivize non-CN countries' involvement in climate mitigation efforts and assist policymakers in determining the necessity of BECCS deployment.

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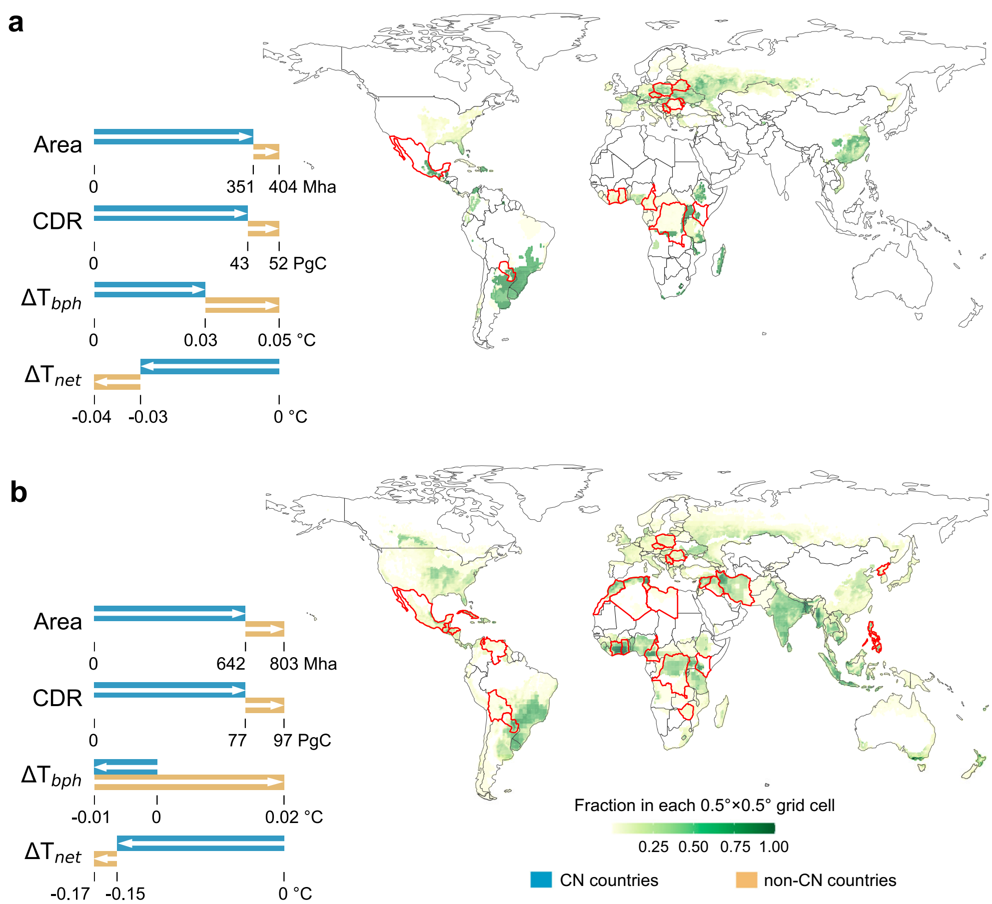

Fig. 1 | Bioenergy crop cultivation maps and contributions of CN and non-CN countries to global climate mitigation. The cultivation maps from MAgPIE under the low-warming (**a**) and overshoot (**b**) scenarios are derived directly from the Land-Use Harmonization 2 (LUH2) dataset[18]. The bars on the left represent the contributions of CN and non-CN countries to the global total bioenergy crop cultivation area, net carbon-dioxide removal (CDR), biophysical air temperature change (ΔT_{bph}) and net air temperature change (ΔT_{net}). Blue bars represent changes when cultivating switchgrass in the CN countries only, and yellow bars represent further changes when cultivating switchgrass in both CN and non-CN countries. Arrows represent the directions of changes. The non-CN countries with a cultivation area > 1 ha are marked in red. Note the scales in the bar plot are different between (**a**) and (**b**).

To attain carbon neutrality goals, the adoption of negative emission technologies such as BECCS is indispensable. By substituting biomass for fossil fuels in energy generation and capturing CO_2, BECCS provides great CDR potentials. Here, we use an Earth system model (ESM) with an explicit representation of bioenergy crops[14,16] to simulate the contribution of non-CN countries to the global temperature change in future BECCS scenarios. The model simulations have been validated against field measurements and satellite data (Supplementary Text 1). We consider two BECCS scenarios where BECCS is the main CDR option. The first one is a low-warming scenario based on Shared-Socioeconomic Pathway (SSP) 2 and Representative Concentration Pathway (RCP) 2.6 (hereafter, the low-warming scenario), reflecting current socio-economic trends and moderate policy interventions, aimed at achieving the 2 °C warming goal under existing commitments. The second one is an overshoot scenario based on SSP5 and RCP3.4 (hereafter, the overshoot scenario), envisioning a future where global temperatures initially exceed the target, peaking at ~2.5 °C, before being reduced to the desired level through strong mitigation measures (Methods). We adopt these two scenarios because they represent different future pathways (i.e., keeping low-warming until 2100 versus temperature overshooting first and then declining), and both need strong negative emission technologies such as BECCS to remove atmospheric CO_2. The global cultivation maps in these two scenarios are derived from the IAM MAgPIE[17], which implements bioenergy crop cultivation globally in both CN and non-CN countries (Fig. 1) based on cost minimization principle, suitable land use types and socio-economic factors integrated within the SSP-RCP scenarios. We used gridded data of future bioenergy crop cultivation maps for MAgPIE directly from the Land-Use Harmonization 2 (LUH2) dataset[18]. We then overlaid the maps of CN and non-CN countries (Supplementary Fig. 1) onto the gridded cultivation map, to separate the cultivation regions for CN and non-CN countries. The cultivation area of bioenergy crops in the low-warming scenario in 2100 is about half of that in the overshoot scenario (Fig. 1), because substantial BECCS will be implemented after 2040 to offset the overshoot emissions in the latter scenario[18]. The second-generation bioenergy crops such as switchgrass, are considered a crucial component in future climate mitigation scenarios by IAMs, due to its higher biomass yields, lower input requirements, and ability to grow on marginal lands and higher energy efficiency[16,17]. In this study, we assumed switchgrass over the BECCS regions (Fig. 1). Switchgrass is explicitly described in the land surface model with parameters calibrated from field data[16]. The net CDR is the sum of harvested biomass, CCS loss and LUC emissions caused by the bioenergy crop cultivation (Supplementary Equation (1-4)), and it is further translated into biogeochemical air temperature change using the OSCAR ESM emulator[19] (Methods). The biophysical air temperature change is simulated by the coupled ESM (Methods). The net air temperature change is thus the sum of biogeochemical and biophysical temperature change[13] (Eq. 1 in Methods). We assume that the CN countries would cultivate bioenergy crops in order to realize the carbon neutrality commitment, on the top of which, non-CN countries may or may not cultivate bioenergy crops. Accordingly, we conduct simulations to quantify the contribution of non-CN countries by comparing simulations where switchgrass is cultivated in both CN and non-CN countries with simulations where it is only cultivated in the CN countries (Methods).

Results

Contribution of non-CN countries at the global scale

The non-CN countries account for 14% and 20% of the global total bioenergy crop cultivation area under the low-warming and overshoot scenarios (408 Mha and 803 Mha, respectively, Fig. 1 and Supplementary Fig. 2). Their cumulative CDR until 2100, calculated as the difference between the simulations where switchgrass is cultivated in both CN and non-CN countries and the simulations where it is cultivated only in the CN countries, is non-negligible, reaching 9.1 ± 2.8 (95% confidence interval, CI) PgC and 19.9 ± 5.2 PgC for the low-warming and overshoot scenarios. The corresponding proportions of global total CDR from BECCS in non-CN countries are 17% and 20%, higher than their proportions of cultivation area. In terms of biogeochemical temperature changes resulting from CDR, the contribution of non-CN countries is even more pronounced. The biogeochemical effects from CDR of additional cultivation in these non-CN countries will reduce global average temperature by 0.03 ± 0.04 °C and 0.05 ± 0.06 °C (30% and 27% of the total reduction) in the low-warming and overshoot scenarios (Supplementary Fig. 11).

Despite the biogeochemical cooling effects, the overall biophysical effect of further switchgrass cultivation in non-CN countries is warming in both scenarios. Under the low-warming scenario, the biophysical effects of cultivation in the non-CN countries contribute a temperature increase of 0.02 ± 0.01 °C (from 0.03 ± 0.02 °C when only cultivation in CN countries to 0.05 ± 0.03 °C when cultivation in all countries). Under the overshoot scenario, by contrast, switchgrass cultivation in CN countries will cool the lands by 0.01 ± 0.01 °C through biophysical feedbacks. However, the biophysical effect of cultivation in non-CN countries will increase the temperature by 0.03 ± 0.02 °C, leading to an overall increase of 0.02 ± 0.01 °C with cultivation in all countries.

Combining the biogeochemical effects from CDR and the biophysical effects, the net air temperature change over lands is −0.03 ± 0.07 and −0.15 ± 0.17 °C in the low-warming and overshoot scenarios with switchgrass cultivation only implemented in the CN countries. Cultivation in the non-CN countries will further contribute a cooling effect of 0.01 ± 0.04 °C and 0.02 ± 0.06 °C in these two scenarios, because its biogeochemical cooling effect (−0.03 ± 0.04 and −0.05 ± 0.06 °C) is partly counterbalanced by biophysical warming effect (0.02 ± 0.01 and 0.03 ± 0.02 °C). The overall contribution of non-CN countries to the net temperature reduction is 25% and 12% under the low-warming and overshoot scenarios, implying that the non-CN countries play a more important role in mitigating climate in the low-warming scenario than the overshoot scenario.

Contribution of non-CN countries in each region

At the regional scale, the air temperature changes show strong variations (Fig. 2a). Assuming that switchgrass is cultivated in the CN countries, further cultivation in the non-CN countries leads to an extra cooling (or nearly zero) effect in most regions under the two scenarios. However, it causes extra warming in western Europe and Eurasia in both scenarios, and in Eastern Asia and South Asia only in low-warming scenario, implying more challenges in controlling temperature increase in these regions. We also find that the extra air temperature change and the additional cultivation area in the non-CN countries are decoupled geographically. For instance, there is no additional cultivation area in Pacific developed region (Fig. 2b and c), but the temperature of this region would be reduced substantially if cultivation occurs in remote non-CN countries (Fig. 2a).

In the low-warming scenario, additional cultivation area in the non-CN countries is primarily located in Africa, South and central America, Western Europe, and Eurasia (Fig. 2b). However, further cultivation of switchgrass in the non-CN countries leads to considerable warming effects in Western Europe and Eurasia, primarily contributed by the biophysical warming effect (Supplementary Fig. 12). Additionally, in the low-warming scenario, although the cultivation area in the non-CN countries in North America is marginal, it exhibits noticeable reduction in net air temperature after further cultivation in the non-CN countries, primarily attributed to the biophysical cooling effect (Supplementary Fig. 12).

In the overshoot scenario, the cultivation area of non-CN countries is lower in Eurasia, South Asia, and Western Europe but higher in Africa (Fig. 2c). However, after additional switchgrass cultivation in the non-CN countries, the net air temperature change in Africa remains relatively small (Fig. 2a), despite the higher CDR contributed by the non-CN countries (Supplementary Fig. 10). Further cultivation in the global non-CN countries induces a strong biophysical warming effect in Western Europe (Supplementary Fig. 12), leading to a net air temperature increase (Fig. 2a).

Temperature changes in countries

We further analyze the net air temperature change in the non-CN countries with the largest cultivation area (e.g., Democratic Republic of the Congo, Mexico, and Paraguay in the low-warming scenario; Iran, Republic of Côte d'Ivoire, and Cameroon in the overshoot scenario, Fig. 3a, b), and the temperature changes in the CN countries (e.g., Afghanistan, Nepal, and Ukraine in the low-warming scenario; Bhutan, Bulgaria, and Hungary in the overshoot scenario) that are most affected (i.e., largest absolute temperature change) by the additional cultivation in non-CN countries (Figs. 3c, d; Supplementary Data 1). Note the top ten countries in the low-warming scenario are different from those in the overshoot scenario due to the different bioenergy crop cultivation maps (Methods). In the low-warming scenario, 7 out of the top 10 non-CN countries experience an extra warming with switchgrass cultivation in the non-CN countries, and the warming magnitude in these 7 countries (e.g., Belarus) is much larger than the cooling magnitude in the remaining 3 countries with an extra cooling (orange arrows in Fig. 3a). By contrast, 7 out of the top 10 CN countries show a temperature reduction with additional cultivation in the non-CN countries (Fig. 3c), indicating further benefits of cooling in these CN countries. In the overshoot scenario, 4 and 3 out of the top 10 non-CN countries show an extra moderate cooling and warming after additional cultivation in all non-CN countries, and the temperature change in other countries is minor (Fig. 3b). However, the impacts of further cultivation in the non-CN countries on the top 10 most affected CN countries are very strong in the overshoot scenario, ranging from 0.58 to 1.13 °C (except Bhutan) (Fig. 3d). These changes are driven by biophysical effects (Supplementary Fig. 6) due to the altered land surface properties such as albedo and evapotranspiration by bioenergy crop cultivation. These local energy changes further impact other regions through the atmospheric circulation, which redistribute energy spatially. It should be noted that some non-CN countries (e.g., Iran and Cameroon) and CN countries (e.g., Russia) have large cultivation area, but the CDR is low due to lower biomass yields in regions with unfavorable climate conditions (Supplementary Fig. 7, Supplementary Fig. 8b, c).

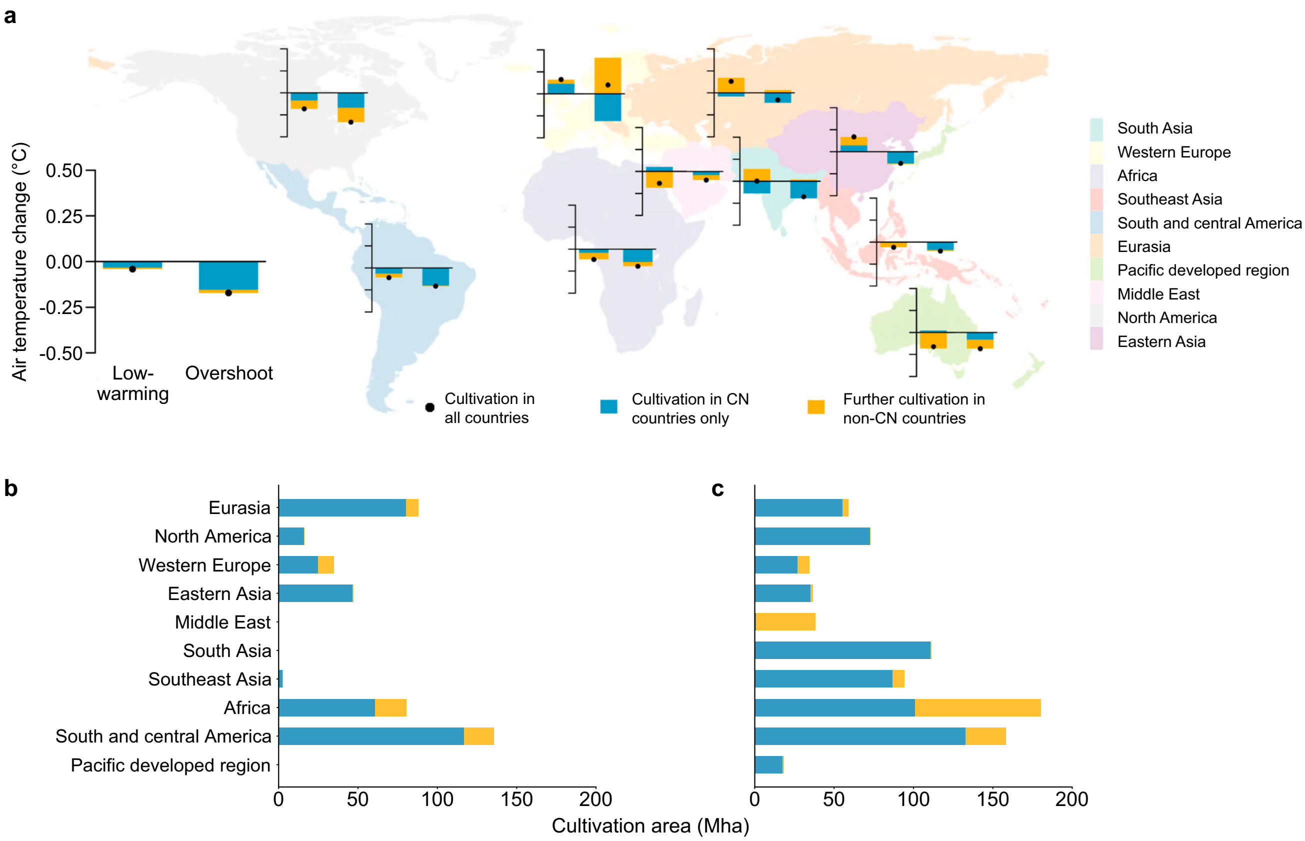

Fig. 2 | Contributions of CN and non-CN countries to net air temperature change and cultivation area at the regional scale. In (**a**), blue bars represent the net air temperature change when cultivating switchgrass in the CN countries only, and orange bars represent the temperature changes after further cultivation in the non-CN countries. In (**b**) and (**c**), blue bars indicate the cultivation area in the CN countries within each region, and orange bars indicate the further cultivation area in the non-CN countries under the low-warming (**a**) and overshoot (**b**) scenarios.

Comparison with eucalypt cultivation as an alternative bioenergy crop

In addition to switchgrass, we also test a woody crop, eucalypt, using the same simulation setup as switchgrass (Supplementary Text 7). Compared to switchgrass, eucalypt has higher CDR potentials in both CN and non-CN countries due to its higher yields, and results in a stronger biogeochemical cooling effect (Supplementary Fig. 15). The biophysical temperature changes by eucalypt cultivation are opposite to those by switchgrass cultivation (Supplementary Fig. 15). The biophysical effect of eucalypt cultivation in the CN-countries is cooling in the low-warming scenario and warming in the overshoot scenario. The contribution of additional eucalypt cultivation in the non-CN countries is found to be negligible in the low-warming scenario and a strong biophysical cooling effect in the overshoot scenario. Therefore, the overall contribution of non-CN countries to the net temperature change is 0.05 ± 0.04 and 0.13 ± 0.11 °C for eucalypt in the low-warming and overshoot scenarios, much higher than 0.01 ± 0.04 and 0.02 ± 0.06 °C for switchgrass. It thus reinforces the important role of the non-CN countries in global climate mitigation.

Discussion

In this study, we explore the distinct contributions of non-CN countries to the global climate mitigation potential of BECCS in both the low-warming and overshoot scenarios. It is different from the previous study[14] that focused only on the low-warming scenario. More importantly, the contribution of non-CN countries to the biophysical temperature changes cannot be simply deduced from the simulation with BECCS implementation in all countries[14], and it requires factorial simulations performed in this study (Supplementary Text 4). In terms of potential cultivation area for implementation, the cultivation maps we used (408 Mha and 803 Mha in the low-warming and overshoot scenario, respectively) align with the cultivation area range reported in other studies[5,17,20,21]. The corresponding cumulative CDR estimates during 2015–2100 (52.6 ± 8.5 and 111.7 ± 18.1 PgC for switchgrass and eucalypt in the low-warming, 97.5 ± 17.4 and 170.0 ± 30.3 PgC in the overshoot scenarios, respectively) also fall within the broad range of 27 ~ 319 PgC until 2100 reported in a literature review by Minx et al.[22], but they are smaller than the 130 PgC projected by IAMs for the RCP2.6 scenarios[1,2]. This discrepancy is mainly because, compared to IAMs, our model has explicit processes of bioenergy crops and accounts for the full components in the land use change emissions. A previous study using the LPJml model, which also has explicit representations of bioenergy crops, estimated the global cumulative CDR potentials of BECCS to be 68 ~ 111 PgC under SSP2 and 274 ~ 329 PgC under SSP5[10]. Their estimates are slightly higher than ours due to the more optimistic assumptions on the availability and utilization of biomass residues to maximize the BECCS potential. By contrast, our study focuses more on the regional contributions and additionally considers the biophysical effects.

Our results are based on simulations from the ESM with explicit processes for bioenergy crops[14,16]. However, there are some uncertainties due to the simulation set-up and missing processes in the model (Supplementary Text 6). For example, the amounts of CDR in different bioenergy crop cultivation scenarios were calculated using the response curves of various carbon pools derived from the offline simulations. It ignores the impact of future climate change on the bioenergy crop biomass production. In addition, BECCS has other costs such as post-harvest processing such as baling and pelleting[23],

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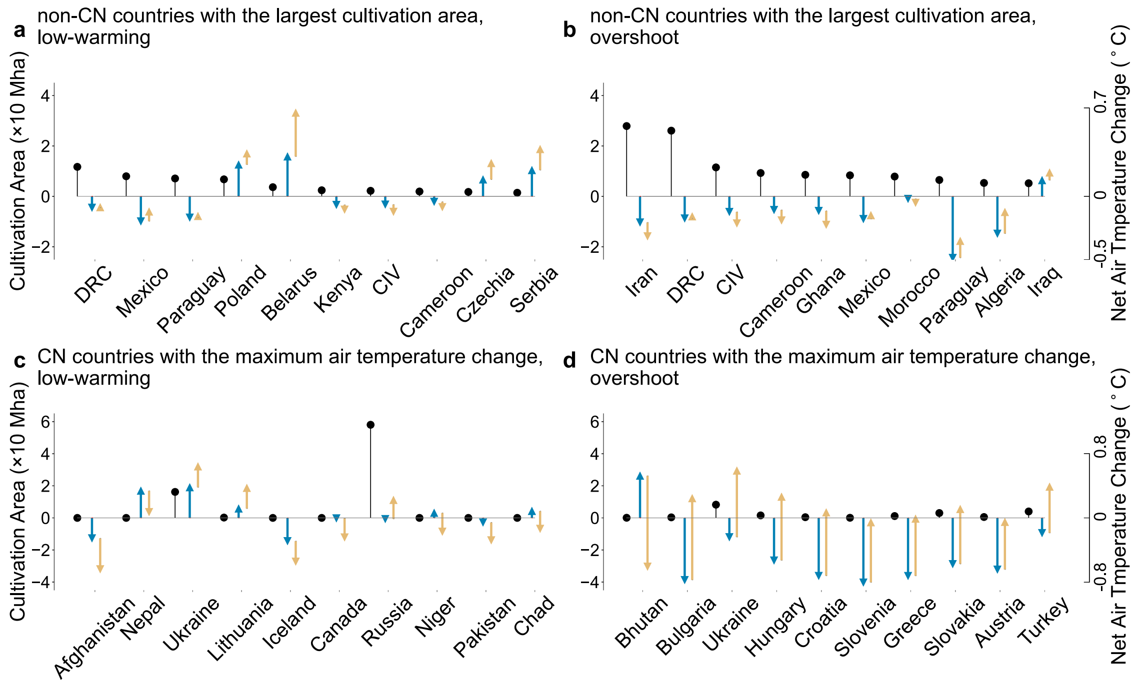

Fig. 3 | The cultivation area and net air temperature change in representative countries. The four panels show the top ten non-CN countries with the largest cultivation area and the top ten CN countries with the maximum net air temperature change under the low-warming (**a**, **c**) and overshoot (**b**, **d**) scenarios. Blue arrows refer to the net air temperature change when cultivating switchgrass in the CN countries only, and orange arrows indicate the temperature changes after further cultivation in the non-CN countries. The directions of arrows represent increase and decrease in air temperatures. Black dots in (**a**–**d**) indicate the cultivation area in each country. DRC and CIV are the Democratic Republic of the Congo and the Republic of Côte d'Ivoire.

transportation from the cultivation area to processing plants, pyrolysis plants and power plants[23–25], and its conversion to available energy[23]. All these additional economic constraints are not explicitly considered in our study. Although downstream operations like grinding and pelleting contribute to energy losses (5 ~ 17% of production costs), these impacts are relatively small, with total efficiency losses ranging from 7.9% to 10.7%[26]. While transportation is a notable contributor to energy losses, it is largely accounted for within the CCS efficiency values reported in the literature[2,7,26,27].

Despite uncertainties in our CDR estimates and temperature changes arising from the idealized assumptions, our results indicate that the absence of BECCS implementation in the non-CN countries could lead to an increase in global temperatures by 0.01 ± 0.04 to 0.02 ± 0.06 °C and a loss of 9.1 ± 2.8 to 19.9 ± 5.2 PgC in global CDR capacity for switchgrass (0.05 ± 0.04 °C to 0.13 ± 0.11 °C and 111.7 ± 18.1 to 170.0 ± 30.3 PgC for eucalypt). The contribution of these countries can exceed their proportion of cultivation area, highlighting the importance of their participation in global climate strategies. The additional cultivation of switchgrass and eucalypt in non-CN countries would induce an overall substantial biogeochemical cooling effect. Although this cooling effect will be partly offset by its biophysical warming effect, the net effect is cooling at the global scale (Fig. 1a). Therefore, taking the biophysical effects into account, the contribution of additional cultivation in non-CN countries to global air temperature reduction will be weakened but still a net cooling effect, implying the non-negligible role of these countries in mitigating climate change. At the regional scale, some non-CN countries (mostly developing countries such as Mexico, Poland and Paraguay) suffer an extra warming while some CN countries gain extra cooling from cultivation in the non-CN countries, which may aggravate the inequality between the CN and non-CN countries. In addition, the relative contribution of non-CN countries to the global and regional temperature reduction is greater in the low-warming scenario than that in the overshoot scenario for switchgrass. Therefore, avoiding the overshooting of temperature will not only reduce cost for climate change mitigation but also strength the effectiveness of implementing BECCS in the non-CN countries. The implementation of bioenergy crop cultivation is not likely synchronized across countries, and a delayed implementation may lead to a decrease in CDR and ultimately reduce the effectiveness of BECCS as a climate mitigation strategy[28] (Supplementary Text 6).

The CDR potential of BECCS deployment in the non-CN countries shows their non-negligible potential contributions to global carbon reductions if these countries would adopt net-zero goals and implement BECCS, underscoring the necessity of setting and pursuing the carbon neutrality targets through proper mitigation measures. But it needs to enhance collaborative efforts in technology sharing and capacity building. It is also important to consider the unintended biophysical impacts, such as regional warming caused by remote bioenergy crop cultivations, which could exacerbate inequalities between countries. To mitigate these effects, we recommend developing regional policy frameworks that not only promote the adoption of BECCS but also incorporate measures to monitor and manage both local and remote biophysical impacts. Therefore, our study advocates for a more integrated approach in international climate negotiations, ensuring that the contributions and capacities of both CN and non-CN countries are acknowledged and effectively utilized. For countries with a lower CDR per cultivation area, it is crucial to understand the complex interplays between the bioenergy crop cultivation area and the corresponding impacts on regional climate change with additional specific coupled simulations (Supplementary Text 8). Additional coupled simulations would be needed to explore how global temperatures would be affected by excluding bioenergy crop cultivation in countries with lower CDR per cultivation area. Future studies could also explore the synergistic effects of mixed bioenergy crop systems that include a variety of regionally adapted bioenergy crops, better reflecting diverse geographic and climatic conditions. Such analyzes could provide deeper insights into the effectiveness of regional BECCS

Table 1 | Simulation design for switchgrass cultivation in this study

Name	Scenario	Cultivation countries	Biogeochemical effect	Biophysical effect
Bioenergy crop cultivation simulations	Low-warming	CN countries	√	√
	Overshoot	CN countries	√	√
	Low-warming	CN countries + non-CN countries	√	√
	Overshoot	CN countries + non-CN countries	√	√
Reference simulation	/	CN countries + non-CN countries		√

implementation and assist policymakers in making informed strategic decisions regarding its deployment.

Our study provides a framework for assessing the roles of non-CN countries in land-based climate mitigation options such as afforestation, and using bioenergy crop cultivation as an example, demonstrates the importance of their efforts in global climate mitigation. While BECCS is a critical technology for achieving carbon neutrality, other land-based CDR strategies such as afforestation and reforestation, and soil carbon sequestration are also important[29]. These strategies could provide additional CDR capacities, especially in regions where BECCS may be less effective or infeasible, and they may also help enhance the resilience of climate mitigation strategies across the varying ecological and socio-economic contexts. Collaborative international strategies are advocated to harness the full potential of these mitigation measures in achieving carbon neutrality. However, it also involves complex political challenges, which require a balance of economic trade-offs, especially in land use where agricultural needs, conservation efforts, and land-based CDR strategies (e.g., bioenergy crop cultivation) often compete[30–35]. Moreover, political will varies across regions, influenced by differing national priorities, economic capabilities, and policy agendas, all of which impact the feasibility and pace of climate neutrality efforts[36–38].

Methods

Simulation scenario design

The status of carbon neutrality target for each country is downloaded from https://zerotracker.net/, and there were 136 countries with a carbon neutrality target but at different degrees of progress by the end of November 2021 (achieved, in law, in policy document, declaration / pledge, proposed / in discussion, Supplementary Fig. 1). In our study, "no-target" countries refer to those without any plans for carbon neutrality. Countries with "proposed / in discussion" targets may already be initiating the plans and preliminary steps towards carbon neutrality, and they are assumed to reach a target and take action in climate mitigation eventually in this study. We chose switchgrass as the representative bioenergy crop in the main results due to its broader environment adaptability and lower cultivation requirements than some woody corps[14,16,39–42]. Although other herbaceous bioenergy crop types such as miscanthus may have higher yields than switchgrass, most field measurements of miscanthus were conducted in Europe[16], and it is expected to have much higher yields in the tropics with more favorable climate conditions but without validations. Considering the limitations in agricultural management in these non-CN countries (most located in the tropics, Fig. 1), we chose switchgrass with a more realistic yield range as an example in this study. Switchgrass is assumed to be cultivated synchronously in all CN countries or in both CN and non-CN countries. In order to separate the contribution of non-CN countries to the biophysical temperature change, we ran two sets of simulations: bioenergy crop is cultivated 1) in the CN countries only and 2) in both CN and non-CN countries. Their difference is thus the contribution of non-CN countries.

We designed four bioenergy crop cultivation scenarios based on two bioenergy crop cultivation maps and either cultivating in the CN countries only or in both CN and non-CN countries and a reference scenario without bioenergy crop cultivation (Table 1, Supplementary Text 4). The contribution of non-CN countries is calculated as the difference between the simulations where switchgrass is cultivated in both CN and non-CN countries and the simulations where switchgrass is only cultivated in the CN countries in a given SSP-RCP scenario (Table 1). The cultivation maps (Supplementary Fig. 2) were the BECCS scenarios from the integrated assessment model of MAgPIE[18], in which BECCS serves as the main negative emission technology to limit global warming (Supplementary Text 2). The cultivation maps generated by MAgPIE were based on the SSP-RCP scenarios, which integrated future land use changes and socio-economic developments. This approach ensures that the allocation of land for bioenergy crops is both economically viable and consistent with projected land use changes, thereby reflecting a comprehensive assessment of potential cultivation land areas under different future scenarios. The low-warming and overshoot scenarios represent different trajectories with global climate mitigation actions, with varying degrees of reliance on BECCS. The low-warming scenario, based on "a middle-of-the-road" pathway (SSP2), follows current socio-economic trends with moderate policy interventions, aiming to stabilize radiative forcing at 2.6 W m^{-2} by 2100 to keep global warming well below 2 °C[43]. This scenario helps evaluate the realism of achieving the 2 °C climate goal with existing commitments. In contrast, the overshoot scenario, based on the "fossil-fueled development" pathway (SSP5) until 2040, is characterized by high socio-economic growth and energy demand predominantly met through fossil fuels, and then followed by CDR, leading to a higher radiative forcing level of 3.4 W m^{-2}[44]. It represents a situation where the temperature exceeds target thresholds before aggressive reductions, thereby examining the emergency response capabilities and long-term impacts of aggressive negative emissions technologies, especially in contexts where immediate mitigation is politically or economically unfeasible. These scenarios are particularly valuable in their ability to represent a range of possible futures, from moderate progress and stabilization to high-growth and aggressive mitigation, providing a comprehensive view of the varied levels of urgency and policy adaptations in achieving global climate targets. The cultivation area of bioenergy crop was translated into a bioenergy Plant Functional Type (PFT) fraction in each grid cell used in the simulations by ORCHIDEE-MICT-BIOENERGY. Note that the competition between energy crops and other crops was determined by MAgPIE, not by ORCHIDEE-MICT-BIOENERGY. MAgPIE dynamically optimizes land allocation based on economic and policy conditions to minimize the total cost of agricultural production for a given demand for food and bioenergy[45]. It allocates land between other crops (food crops mainly) and energy crops by considering both the cost of land conversion and the potential for yield-increasing technological changes. This economic optimization ensures that land allocation decisions are cost-effective and reflect the economic realities of agricultural production under various scenarios.

To make the PFT maps in our simulations, we first calculated annual land use changes based on the MAgPIE output from LUH2, which documents annual area of each land use type in each grid cell. Note the land use change data from LUH2 may be slightly different from those from the MAgPIE outputs due to the harmonization processes[18]. For grid cells designated for bioenergy crops, the increase in the bioenergy crop cultivation areas was proportionally taken from the original vegetation types, ensuring that the expansion of bioenergy crops accurately reflects decreases in the existing land cover types. The CDR was then calculated by multiplying the area change and the carbon changes from the corresponding response curves after a given land use change type (e.g., from cropland to switchgrass) in each grid cell (detailed in Supplementary Text 3.1). Cropland is the predominant land cover source for bioenergy crops, reflecting that MAgPIE strongly relied on cropland to meet bioenergy demands (Supplementary Fig. 4, Supplementary Fig. 2). Moreover, the overshoot scenario shows a marked increase in the conversion area starting around 2040, indicating a substantial expansion in bioenergy crop cultivation as the key deep decarbonization measure. For the coupled model simulations, we used a reference PFT map derived from the satellite-based CCI land cover data[46]. This map was adapted to include bioenergy crops by the year 2100. In each grid cell, we converted the corresponding source PFTs to the bioenergy crop PFT based on the land use transitions from MAgPIE. The PFT maps were maintained statically at the year 2100 conditions throughout the simulations of biophysical effects.

Estimation of CDR

Following Wang et al.[13], the offline simulations for the carbon dynamics were performed using ORCHIDEE-MICT-BIOENERGY, a dynamic vegetation model with an explicit representation of bioenergy crops[16] (Supplementary Text 3). In the offline simulations, ORCHIDEE-MICT-BIOENERGY simulated the changes in biomass and soil carbon pools resulting from the conversion of different vegetation types to bioenergy crops. Response curves for LUC types (from forest, grass, pasture, and cropland to switchgrass) were derived from these offline simulations, used for calculating CDR (including harvested biomass, LUC carbon emissions and CCS loss, Supplementary Text 3.1) under bioenergy crop cultivation scenarios. We used CCS efficiency values from literature[1,6–10,47–49] to implicitly represent the emissions from operational costs, biomass, and CO_2 transportation and losses during CCS.

Besides, the CDR from bioenergy crops relies on regular harvests, impacting soil fertility[50]. We replenished nitrogen loss through fertilizer application, considering GHG emissions from fertilizer production and N_2O emissions. The study accounts for CO_2 reduction, fertilizer-related emissions, and N_2O emissions, estimating soil nitrogen loss and applied fertilizer amounts in different scenarios (Supplementary Text 3.2).

Estimation of the temperature change

The CDR were further translated into biogeochemical temperature changes using the compact ESM[19] (OSCAR, Supplementary Text 3.3). OSCAR simulated temperature changes related to CDR processes and GHG emissions from fertilization, considering modeling uncertainties with a sample size of 2000. Global biogeochemical cooling effects were calculated by aggregating regional outputs.

The biophysical temperature changes were simulated by the coupled land-atmosphere model IPSL-CM[51], in which ORCHIDEE-MICT-BIOENERGY serves as the land surface model[14], LMDz (v6) served as the atmosphere model[52,53] (Supplementary Text 4). Ocean and sea-ice models were not activated. The simulations, spanning 50 years with 2014 atmospheric CO_2 levels[46,54], employed a spatial resolution of 1.26° × 2.5°. The study conducted five coupled simulations, including switchgrass cultivation scenarios in the CN and non-CN countries under the low-warming and overshoot scenarios, and a reference simulation without bioenergy crops (Table 1). The simulations reached a steady state between the fifth and tenth years for switchgrass, and results from the last decade (41st to 50th years) were analyzed for biophysical effects. The cultivation map in 2100 was used for the simulations of biophysical effects.

The net air temperature change (ΔT_{net}) induced by switchgrass cultivation in this study includes 1) biogeochemical effects from the CDR of BECCS and the fertilization related greenhouse gas emissions (Supplementary Text 3) and 2) biophysical effects from the changed local energy budget and the altered atmosphere circulation (Supplementary Text 4):

$$\Delta T_{net} = \Delta T_{bgc} + \Delta T_{bph} \quad (1)$$

The subscript represents the air temperature contributed by the biogeochemical effects ("bgc") or the biophysical effects ("bph").

Uncertainty estimation

To account for the uncertainties inherent in the CDR estimation, we conducted an analysis using Monte Carlo methods (Supplementary Text 6), which included uncertainties in bioenergy yield estimations, SOC change simulations, and CCS efficiencies. We estimated the 1-σ uncertainty in CDR and reported the uncertainties as the 95% confidence intervals by assuming a normal distribution (Supplementary Text 6.1). For the uncertainties in the biogeochemical temperature changes, we derived the 95% confidence intervals from the OSCAR simulation outputs generated by 2000 times parameter sampling (Supplementary Text 6.2). It should be noted, however, some other uncertainties (e.g., biophysical temperature change, impacts of climate change on biomass production, other GHG emissions) are discussed but not accounted for in this study (Supplementary Text 6.3–6.4).

Data availability

The data supporting the main findings of this study are provided in Figshare through the following link https://doi.org/10.6084/m9.figshare.26056012. The corresponding coding scripts are available from Code Ocean through https://doi.org/10.24433/CO.6263169.v1. Source data are provided with this paper.

Code availability

The source code of ORCHIDEE-MICT-BIOENERGY is publicly accessible and can be found at https://doi.org/10.14768/02v2-z742. Additional details and ongoing developments about the ORCHIDEE land surface model are available on the project homepage at https://orchidee.ipsl.fr/. This model is governed by the CeCILL license under French law, adhering to the principles of free software distribution. Users are permitted to use, modify, and redistribute the software in accordance with the CeCILL license, as distributed by CEA, CNRS, and INRIA, detailed at http://www.cecill.info.

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W.L., J.W. and P.C. designed the study, J.Z., W.L. and J.W. carried out the modeling and analysis. J.Z., W.L. and J.W. wrote the first draft. P.C., T.G., Z.L., L.Z., M.H., J.H., M.S., L.L., X.H. contributed to the interpretation of the results, the draft revision and the computational tools.

Competing interests
The authors declare no competing interests.

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