communications earth & environment

Article

https://doi.org/10.1038/s43247-025-02033-6

Multiple planetary boundaries preclude biomass crops for carbon capture and storage outside of agricultural areas

Check for updates

Johanna Braun [1] ✉, Constanze Werner[1], Dieter Gerten[1,2,3], Fabian Stenzel [1,4], Sibyll Schaphoff[1] & Wolfgang Lucht [1,2]

Six of nine planetary boundaries are currently transgressed, many related to human land use. Conversion of sizeable land areas to biomass plantations for Bioenergy with Carbon Capture and Storage (BECCS) – often assumed in climate mitigation scenarios to meet the Paris Agreement – may exert additional pressure on terrestrial planetary boundaries. Using spatially-explicit, process-based global biogeochemical modelling, we systematically compute feedstock production potentials for BECCS under individual and joint constraints of the planetary boundaries for nitrogen flows, freshwater change, land system change and biosphere integrity (including protection of remaining forests), while reserving current agricultural areas for meeting the growing global demand for food, fodder and fibre. We find that the constrained BECCS potential from dedicated *Miscanthus* plantations is close to zero (0.1 gigatons of carbon dioxide equivalents per year under mid-century climate for Representative Concentration Pathway (RCP) 4.5). The planetary boundary for biosphere integrity has the largest individual effect, highlighting a particularly severe trade-off between climate change mitigation with BECCS and ecosystem preservation. Ultimately however, the overall limitation results from the joint effect of all four planetary boundaries, emphasizing the importance of a holistic consideration of Earth system stability in the context of climate change mitigation.

The IPCC's 6th assessment report on the mitigation of climate change reinforced that, along with rapid and stringent decarbonization, carbon dioxide removal (CDR) will be required to reach net zero greenhouse gas emissions in compliance with the Paris climate limits[1]. The feasible and desirable scale and timing of CDR deployment is, however, highly debated[2–8]. To date, cost-optimized scenarios from integrated assessment models limiting warming to 2° or below mostly rely on extensive CDR, often to a large degree from bioenergy with carbon capture and storage (BECCS)[5,9]: simulated annual median BECCS volumes amount to 2.8 $GtCO_2eq\ yr^{-1}$ [0.5–9.5; 5th–95th percentile] in 2050 and 9.0 [2.6–16.2] $GtCO_2eq\ yr^{-1}$ in 2100[1]. In addition to partial use of residual, waste, or forest-based biomass[10], this is mirrored in the strong expansion of bioenergy cropland (for use with or without CCS) by 102–711 Mha from 2020 to 2100[11], equivalent to 6-45% of global cropland area[12]. At the same time, the internationally agreed Sustainable Development Goals and the Kunming-Montreal Global Biodiversity Framework call for substantial strengthening of the protection of nature and its restoration. Given the far-reaching impacts of unsustainably extractive land use for BECCS, additional expansions of biomass plantations for climate change mitigation would likely further increase pressures on the terrestrial biosphere[13–17]. Previous studies have shown that the conversion of (semi-)natural land to bioenergy plantations would strongly impact biodiversity[18–20]. In addition, associated increases in irrigation water use and fertilization can lead to further deterioration of freshwater ecosystems and eutrophication[21–25]. This points to a potentially severe trade-off between preservation and regeneration of the terrestrial Earth system and biomass-based CDR and, thus, a need for sustainability limits on plantation-based BECCS[26,27].

As one structured approach to evaluate such sustainability limits, the planetary boundary (PB) framework offers a multi-dimensional perspective on Earth system stability by suggesting precautionary limits to human interference with nine critical Earth system processes[28]. The PB framework aims to delineate a Holocene-like state of the Earth system as the only state of

[1]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, D-14412 Potsdam, Germany. [2]Department of Geography, Humboldt-Universität zu Berlin, Unter den Linden 6, D-10099 Berlin, Germany. [3]Integrative Research Institute on Transformations of Human-Environment Systems, Unter den Linden 6, D-10099 Berlin, Germany. [4]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden. ✉e-mail: johanna.braun@pik-potsdam.de

which we know that it provides a safe operating space for humanity and the complex processes of civilization that today sustain it[29]. Currently, six of nine PBs are transgressed, some severely[30]. Among these, the strong transgressions of terrestrial PBs are notable (freshwater change, nitrogen flows, land system change, and biosphere integrity). Predominantly, they are caused by agriculture[31,32]. Land-based measures for climate stabilization, while aiming to limit or reverse additional transgression of the climate change PB, could, therefore, substantially add to this pressure and operate at the expense of these non-climatic other pillars of Earth system stability if not appropriately constrained.

To evaluate the PB-compatible potential for the deployment of plantation-based BECCS, a detailed understanding of the interactions with land-based Earth system processes is necessary. Several previous studies have analyzed environmentally sustainable plantation-based bioenergy and/or BECCS potentials in light of possible adverse effects on other aspects of Earth system stability[14,24,33–42]. The estimated sustainable potentials outside of agricultural areas in the absence of a substantial food system transformation range between 5 and 149 EJ yr^{-1} in terms of primary energy content (referring to 2050, except for ref. 24), amongst others depending on the environmental dimensions considered, the comprehensiveness of the resulting constraints on land availability and simulated or estimated biomass yields. With one exception[14], these studies focused on specific environmental dimensions without addressing all relevant PBs. Particularly limits to nitrogen pollution have generally been neglected. As there are, however, considerable trade-offs between protecting one PB and omitting others[13,14,25], it is important to integrate all terrestrial dimensions. In addition, most of the applied constraints do not account for process-based dynamic impacts of the foreseen expansion of biomass plantations. Rather, previous analyses have mostly exempted areas from the deployment of biomass plantations based on static external datasets (e.g., protected areas or water-scarce regions) which neglects temporal changes and dynamic interactions between Earth system processes. Heck et al.[14] were the first to include all terrestrial PB dimensions within their assessment and showed that PB-compatible BECCS potentials would be small due mainly to existing pressures from agriculture (<0.22 $GtCO_2eq\ yr^{-1}$). However, they relied on external data for computing effects on the nitrogen and biosphere integrity PB and did not disentangle the contribution of individual PB constraints to limit BECCS potential. Thus, a systematic process-based modeling of the individual and cumulative constraining effects of the four terrestrial PBs on BECCS potentials in one consistent framework has been missing to date.

Not least, BECCS potential strongly depends on the cultivation location and the carbon content of the replaced natural vegetation, as both initial land use change emissions and gradual changes in soil and litter carbon pools play a role[43]. The higher the "carbon debt"[44] and the lower the simulated yields, the longer the carbon payback period, i.e., the number of years needed to compensate for these land use change emissions[27,45–47]. These findings point to the importance of simulating both yields and land use change emissions based on process-based spatially explicit modeling when deriving potential net CDR from BECCS.

In this study, we, therefore, combine (i) such spatially explicit simulation of yields and land-use change emissions to estimate CDR potentials with the (ii) simulation of resulting impacts on four terrestrial PBs, all within one consistent process-based modeling framework. This allows us to systematically assess theoretical CDR potentials through BECCS from dedicated 2nd-generation biomass plantations under the individual and joint constraints of avoiding additional transgression of terrestrial PBs. In view of the need to provide sufficient food, fiber, and fodder for an additional two billion people by 2050[48], we base this study on the assumption that, as a minimum requirement, current agricultural areas have to remain reserved for this purpose. Therefore, biomass plantations are allowed to only expand into remaining (semi-)natural land in our scenarios, to the extent that the PB constraints would allow. We note that changes in agricultural technologies and demand might affect the extent of agricultural areas[49] and that there might be other well-justified, important (e.g., ecological) reasons for not utilizing (semi-)natural areas. Our study, however, is designed to consistently quantify theoretical ceilings to the order of magnitude of potentials and the effects of trade-offs on the planetary scale.

We simulate CDR potentials from biomass plantations for BECCS under these constraints with the dynamic global vegetation model LPJmL5[50,51]. As employed here, it includes spatially explicit representations of the control variables for relevant terrestrial PBs[31] and an enhanced representation of herbaceous 2nd generation bioenergy crops such as *Miscanthus* (Supplementary Methods). In short—see Methods and Supplementary Information for details—we optimize the spatial distribution and management (rainfed or irrigated, no or optimal fertilizer application) of plantations for maximum CDR provision outside of current agricultural, urban, and protected areas as well as wetlands. Consistent with previous LPJmL-based studies[14,43,46], net yearly CDR potential is simulated based on biomass harvest, while subtracting land use change emissions as well as BECCS supply chain emissions. For the latter, we assess biomass-to-electricity pathways for three different assumed CDR efficiencies based on the MONET CDR optimization model framework[52,53]. We calculate net CDR for a 30-year assessment period under mid-century climate (2036-2065) reaching ~2 °C warming in 2050, by forcing LPJmL with RCP4.5 climate data from five climate models[54].

Next, we further constrain these potentials systematically with each terrestrial PB by considering regional thresholds for nitrogen pollution, freshwater change, land system change and biosphere degradation (Table 1), and assess their respective incremental and cumulative effects on limiting BECCS potentials (see Table 2 for an overview of all scenarios). Taking into account sub-global states of the PB variables acknowledges the strong regional pattern of current PB transgressions[31]. To also consider the implications of these terrestrial PB constraints for the climate change PB, we compare resulting BECCS potentials with CDR rates simulated in scenarios covered in the 6th IPCC assessment report in which global warming is likely limited to <2 °C[1]. We further calculate the carbon payback period for the different scenarios to evaluate the potential for a timely contribution from BECCS, under terrestrial PB constraints, to stabilizing the status of the climate change PB.

This process-based, spatially explicit analysis of multi-dimensional trade-offs between dedicated BECCS plantations for climate change mitigation and protection of the biosphere is to contribute to the debate on the

Table 1 | Applied planetary boundary definitions

Earth system process	Control variable and planetary boundary
Nitrogen flows (PB-N)	N in runoff to surface water as a proxy for dissolved inorganic N concentrations in surface water (max. 2 mg $N\ l^{-1}$ at 0.5° grid cell level)[29,122,123]
Freshwater change (PB-W)	River flow reduction as % of potential mean monthly river flow (max. 25%, 40%, and 55% in low-flow, intermediate-flow and high-flow months, respectively; at 0.5° grid cell level considering upstream-downstream effects)[29,131]
Land system change (PB-L)	Area of forested land as % of potential forest for each biome (min. 85% in tropical and boreal biomes, min. 50% in temperate biomes)[30]
Biosphere integrity (PB-B)	Human appropriation of net primary production (NPP) as a percentage of preindustrial NPP (max. 10%, assessed by biomes, $n = 61$)[30,57]

Planetary boundary (PB) definitions for nitrogen flows, freshwater change, land system change, and biosphere integrity, including the spatial scale of the assessment for constraining the expansion and management of biomass plantations for bioenergy with carbon capture and storage (BECCS). *N* nitrogen.

Table 2 | Simulated scenarios

Scenario name	Description
Agricultural baseline	2017 land use without expansion of biomass plantations
CDRonly	Illustrative reference scenario to maximize carbon dioxide removal by expanding biomass plantations; focus on the climate change PB alone without consideration of trade-offs with terrestrial PBs
+PB-N/+PB-W/…	Biomass plantation expansion and/or management intensification is only allowed, where the respective PB is not yet transgressed in the agricultural baseline, up to the point the regional threshold is reached (see Table 1)
allPBs	All four terrestrial PBs are considered, i.e., biomass plantation expansion and management may not lead to additional transgressions of the regional thresholds
allPBs+	As a more strict implementation of the land system change PB, all remaining (semi-)natural forests are protected from conversion to biomass plantations (*FP* forest protection) in addition to the three other terrestrial PBs

Scenarios for testing the effect of constraining the expansion and management of biomass plantations for bioenergy with carbon capture and storage (BECCS) with terrestrial planetary boundaries (PBs) under mid-century RCP4.5 climate.

volume and limits of responsible biomass-based CDR on land[7,16,27]. We find that if further transgressions of the land and biosphere-related PBs are to be avoided, including protection of remaining forests, and current agricultural areas are safeguarded for food, fiber, and fodder production for a growing world population, BECCS potentials from dedicated plantations are almost zero. While avoiding trade-offs with the biosphere integrity PB poses the strongest constraint on overall CDR potentials, this limitation is ultimately a consequence of the combined effect of all four terrestrial PBs. We conclude that avoiding undesirable trade-offs between climate stabilization and terrestrial PBs for safeguarding the ecological foundations of future generations requires a broader consideration of Earth system stability than expressed by only climate-related carbon balances.

Results

For illustrative purposes, we first computed a theoretical upper ceiling to CDR potential in the absence of environmental constraints, assuming all non-agricultural and biophysically suitable areas (except wetland, protected, and urban areas) were converted to biomass plantations (CDRonly scenario). The implied massive land conversion amounts to 1940 Mha (Fig. 1b), corresponding to ~123% of current arable land[12], and represents far-reaching destruction of remaining (semi-) natural vegetation. For the maximum theoretical CDR potential, 43% of biomass plantations are simulated to be fertilized and 31% irrigated (Fig. 2 and Supplementary Fig. 11), namely where streamflow is abundant throughout the year, and achievable yield benefits are >10%. The fertilization share is not higher due to the limited yield response to fertilization in many locations (in line with observational studies[55,56]). The resulting theoretical ceiling to global CDR potential is simulated to be 42.1 (35.3–52.4) $GtCO_2eq\ yr^{-1}$ (range capturing different assumptions on overall carbon removal efficiency of BECCS and climate forcing from five general circulation models; see Methods and Fig. 1a).

The actual option spaces for biomass plantations—as conceptualized here—depend on PB pressures already present in the agricultural baseline scenario, assuming no land use expansion until mid-century. Regions, where a boundary is already transgressed in this agricultural baseline due to agricultural land use and/or climate change impacts on terrestrial PBs, are blocked for conversion to biomass plantations (see Supplementary Fig. 8 for spatially-explicit terrestrial PB transgressions in the agricultural baseline). In the following, we evaluate both the individual and the combined effects of constraining biomass plantations by each of the four terrestrial PBs considered (in ascending order from the lowest to the highest individual effect simulated).

Nitrogen PB constraint

The PB constraint for nitrogen aims to limit surface water eutrophication[29] (see Table 1). It is here assessed based on simulated nitrogen concentration in runoff from both agricultural and natural land to surface waters as well as its potential alteration due to conversion of (semi-)natural land to biomass plantations. Imposing this constraint alone would lower the global CDR potential by ~20% to 33.4 (28.3–40.7) $GtCO_2eq\ yr^{-1}$ compared to the CDRonly scenario (see Fig. 3). This limitation results primarily from preclusion of biomass plantations where nitrogen PB transgressions occur (on 31% of ice-free land area, e.g., in the US corn belt, north-eastern China, large parts of Europe; Fig. 1b), caused by high fertilizer input in agriculture or by climate change-induced permafrost thawing in the boreal zone that increases runoff and thus nitrogen leaching (Fig. 2 and Supplementary Fig. 8). On remaining areas, the nitrogen PB constraint has only a marginal effect on the relative share of fertilized plantations, as nitrogen use efficiencies are simulated to be relatively high and fertilizer requirements of *Miscanthus* plantations relatively low, consistent with earlier findings[55,56].

Freshwater PB constraint

To prevent additional transgressions of the freshwater PB, monthly river flow reductions caused by biomass plantations due to irrigation and/or changes in local runoff must not reduce the environmental flows required to sustain riverine ecosystems (see Table 1). Applying this freshwater PB constraint in isolation would yield a 59% (57.8–60.3) lower global CDR potential on a 53% smaller plantation area compared to CDRonly (Fig. 1), with irrigated plantation share decreasing from 31% to 20% (see Supplementary Fig. 11). Rainfed plantations are allocated primarily along the East Coast of the US and in Europe, where the freshwater PB constraint severely restricts irrigation (see Fig. 2). Biomass plantation extent is both constrained in regions with climate change-induced environmental flow violations (among others simulated for large parts of Brazil) and in regions with widespread agricultural irrigation and/or other water uses (e.g., parts of eastern China), overall affecting 32% of global ice-free land area. Even rainfed plantations may be precluded in these areas, as their increased evapotranspiration can reduce runoff and, eventually, environmental flows. Furthermore, biomass plantations are disallowed in drylands where irrigation would be required to sustain their growth but where water availability (under environmental flow protection) is insufficient to meet the irrigation demand (e.g., in Australia, the Asian steppes, North Africa, and the Great Plains).

When applying the freshwater PB constraint in addition to the nitrogen constraint, the global CDR potential is cumulatively reduced by ~2/3 (66.2–67.1%) compared to the unconstrained scenario, leaving a potential of 14.0 (11.6–17.6) $GtCO_2eq\ yr^{-1}$ (Figs. 1 and 3a). Remaining cultivation areas are primarily located in the Eastern US, parts of the tropical forests, northern Argentina, southeastern China and Eastern Europe (see Supplementary Fig. 10).

Land system change PB constraint

Complying with biome-specific limits to deforestation defined by the land system change PB (see Table 1)—with spatial allocation of biomass plantations optimized so as to maximize CDR within these limits (Fig. 2)—has a similar effect size as the PB water constraint: Overall CDR is 61% (59.1–62.1) lower than in the CDRonly scenario. This constraint reflects the full

a CDR

Scenario	Incremental: Cumulative CDR reduction (%)	Incremental: Global CDR (Gt CO_2eq yr^{-1})	Single: Isolated CDR reduction (%)	Single: Global CDR (Gt CO_2eq yr^{-1})
CDRonly		42.1 [35.3, 52.4]		42.1 [35.3, 52.4]
+PB-N	-20.7 [-22.3, -19.5]	33.4 [28.3, 40.7]	-20.7 [-22.3, -19.5]	33.4 [28.3, 40.7]
+PB-W	-66.7 [-67.1, -66.2]	14.0 [11.6, 17.6]	-59.3 [-60.3, -57.8]	17.2 [14 , 22.1]
+PB-L	-85.6 [-85.9, -84.9]	6.1 [5.0, 7.8]	-60.6 [-62.1, -59.1]	16.6 [14 , 20.8]
+PB-B	-98.8 [-99.2, -98.2]	0.5 [0.3, 0.9]	-92.7 [-93.1, -92.4]	3.1 [2.6 , 3.9]
+FP	-99.7 [-99.8, -99.6]	0.1 [0.1, 0.2]		

b Biomass plantation area

Scenario	Incremental: Cumulative area reduction (%)	Incremental: Global area (Mha)	Single: Isolated area reduction (%)	Single: Global area (Mha)
CDRonly		1940.2		1940.2
+PB-N	-29.7	1364.7	-29.7	1364.7
+PB-W	-66.4	651.3	-52.6	919.9
+PB-L	-83.2	325.8	-56.9	835.3
+PB-B	-97.4	51.3	-93.6	124.6
+FP	-99.6	6.9		

Fig. 1 | Global net carbon dioxide removal and biomass plantation area under incremental and isolated consideration of terrestrial planetary boundary constraints. Impact of planetary boundary (PB) constraints on net carbon dioxide removal (CDR) (**a**) and biomass plantation area (**b**). See Tables 1 and 2 for the definitions of scenarios and PB constraints (N nitrogen flows, W freshwater change, L land system change, B biosphere integrity, FP forest protection as a stricter definition of the land system change PB). Under these constraints, the distribution of biomass plantations was optimized to maximize net CDR while reserving current agricultural areas for food, fodder and fiber provision. Relative changes refer to the unconstrained CDRonly scenario. For CDR, numbers in brackets depict the range spanned by using inputs from five general circulation models for mid-century climate under RCP4.5 and three carbon removal efficiency pathways (optimal, moderate, low; assuming a biomass-to-electricity conversion). The coloring visualizes the numbers relative to the column's respective maximum values.

protection of (sub)tropical forests in America, Africa, and Asia—covering 18% of ice-free land area—from further conversion given that historical deforestation within these forest biomes is beyond the proposed safe levels. Conversion to biomass plantations is assumed up to the deforestation limit defined by the PB in all other forest biomes, including the tropical forest in the Australasian realm, as well as temperate and boreal forests. This deforestation limit still leads to strong constraints on biomass plantation areas, particularly in central Europe, eastern China, and New Guinea. Overall, the share of biomass plantation area allowed in forest biomes is roughly halved as compared to the CDRonly scenario (from 74% to 38%; Supplementary Fig. 11).

When adding the land system change constraint to the nitrogen and freshwater PB constraint, biomass plantation area decreases by 83% and BECCS potential by 86% relative to CDRonly, yielding 6.1 (5.0–7.8) $GtCO_2$eq yr^{-1} (see Figs. 1 and 3). Remaining plantation areas are found to be concentrated in the eastern US, Eastern Europe, Argentina/Uruguay and sub-Saharan woodland and savanna regions (Supplementary Fig. 10).

Biosphere integrity PB constraint

The PB for functional biosphere integrity sets biome-specific limits to the human appropriation of net primary production (NPP), acknowledging the importance of photosynthetic energy flow for biomes' planetary ecological functions[30,57] (Table 1). This constraint has by far the strongest single effect, reducing both global biomass plantation area and BECCS potential by 93% (Fig. 1). This is due to the fact that high extraction and inhibition of NPP currently already lead to transgressions of the PB in many biomes across the world (Supplementary Fig. 8; on 71% of ice-free land area). Exceptions are confined to the boreal zone, the South American and Australasian rainforest, as well as Australian shrublands, with limited anthropogenic colonization pressure to date. Only 126 Mha of these areas could be converted without further PB transgression, mostly located in forested ecoregions (Supplementary Fig. 11). When focusing on biosphere integrity without adherence to other PBs, the relative share of irrigated plantations in remaining areas is almost double as high as compared to CDRonly (59% vs. 31%) and the relative share of fertilized plantations is also slightly increased (49% vs. 43%), pointing to adverse effects on the PBs for nitrogen flows and freshwater change. Despite the severe restriction in biomass plantation extent, 3.1 (2.6–3.9) $GtCO_2$eq yr^{-1} removal via BECCS would still be possible (Fig. 1).

If the PB for biosphere integrity is considered in addition to the other terrestrial PBs (allPBs scenario), the global CDR potential shrinks to 0.5 $GtCO_2$eq yr^{-1} on 51 Mha of biomass plantations (Fig. 3 and Supplementary Fig. 10), merely 2% of what would be theoretically possible outside of agricultural areas if PB constraints were disregarded (Fig. 1). The potential plantation areas are primarily located in the European boreal zone, filling a small stripe between PB constraints to the south where agriculture already exerts high pressures, and areas with insufficient biomass harvest for net

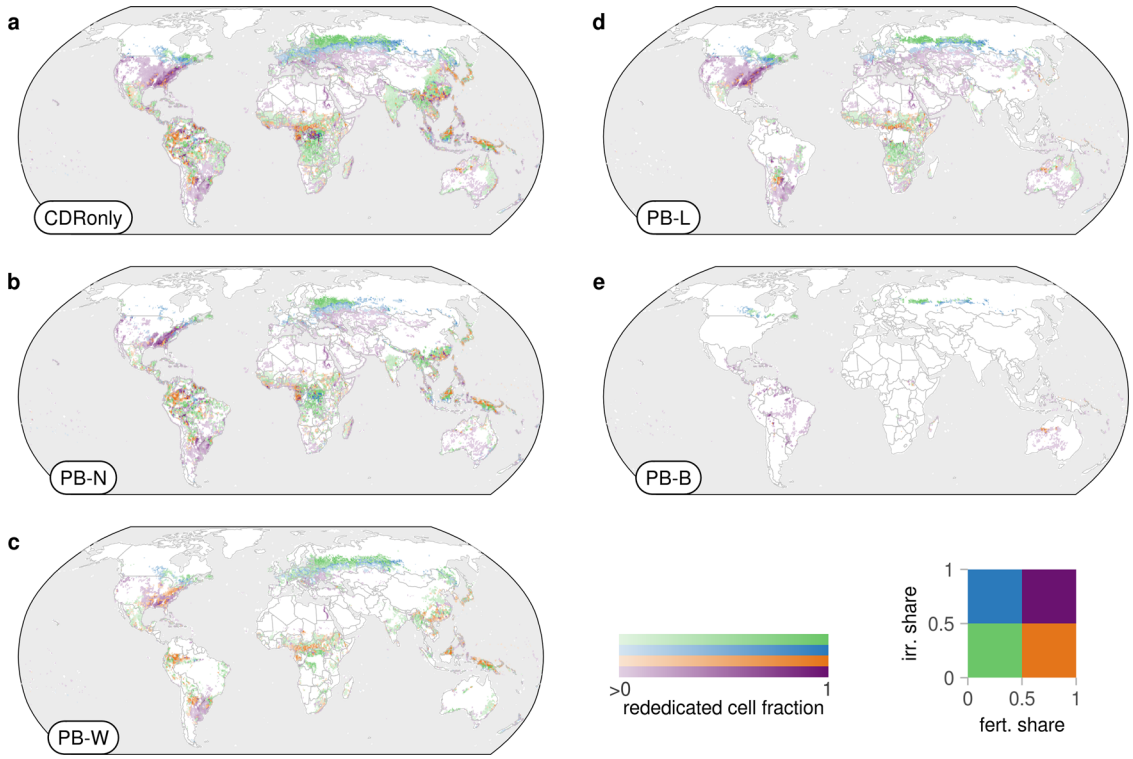

Fig. 2 | Optimized global distribution of biomass plantations to maximize net carbon dioxide removal. Optimized biomass plantation distributions are shown for scenarios without (CDRonly; panel **a**) and with individual planetary boundary (PB) constraints for nitrogen flows (N), freshwater change (W), land system change (L), or biosphere integrity (B) (panels **b**–**e**). Under PB constraints, plantation expansion and/or management is limited by the respective PB thresholds (see Table 1); agricultural areas are safeguarded for food, fodder, and fiber production, and wetlands, urban, and protected areas are excluded from conversion. Colors refer to the share of irrigated vs rainfed (irr. share) and fertilized vs. unfertilized (fert. share) biomass plantations, while the color's transparency represents the cell fraction covered with biomass plantations.

CDR to the north (Supplementary Fig. 10). In other regions of the world only a few small spots are simulated to be suited for biomass plantations (for CDR potentials by world region see Supplementary Table 9).

Full forest protection

While the land system change constraint already strongly restricts conversion of forested ecosystems, the relative share of biomass plantation areas in forested ecosystems is still 87% in the allPBs scenario (Supplementary Fig. 11). Given forest's paramount role in maintaining the natural carbon sink as well as for biosphere integrity, we additionally simulated a scenario (allPBs+) where all currently remaining forest areas (natural and managed) are protected from conversion to biomass plantations, i.e., corresponding to a stricter definition of the land system change PB. This further shrinks the PB-constrained BECCS potential to 0.15 $GtCO_2eq\ yr^{-1}$, with only 6 Mha of potentially available plantation area remaining (Fig. 1). This suggests that terrestrial PB constraints including global forest protection would add up to almost entirely excluding additional biomass plantations assuming that current agricultural land is reserved for future food, fodder, and fiber provision (for a spatial visualization of the incremental constraints, see Supplementary GIF 1). Comprehensively accounting for the combination of multiple environmental constraints in line with a more holistic view of Earth system stability thus severely limits the maneuvering space for plantation-based BECCS.

BECCS potentials in the context of climate change mitigation

The simulated potentials of PB-compatible BECCS from additional biomass plantations (0.15–0.5 $GtCO_2eq\ yr^{-1}$ in the allPBs(+) scenarios) are well below projected CDR demands in scenarios likely limiting warming to 2 °C or below (see Fig. 3b): 7.4 $GtCO_2eq\ yr^{-1}$ in 2050 (5th to 95th percentile: 1.7–15.2 $GtCO_2eq\ yr^{-1}$) and 14.2 (7.1–22.6) $GtCO_2eq\ yr^{-1}$ in 2100[1,11,58]. While this demand may be reached by a portfolio of technologies and practices, BECCS is the most common CDR technology and practice considered in these scenarios[5,9]. Although not differentiating between first- and second-generation bioenergy crops and bioenergy not necessarily being combined with CCS, this is also mirrored in the large increase in bioenergy plantation area assumed in many scenarios: by 118 Mha (18–383 Mha) from 2020 until 2050 and by 302 Mha (102–711 Mha) until 2100[11]. If this expansion would come at the cost of remaining (semi-)natural vegetation, pressures on terrestrial PBs would likely strongly increase, given that the PB-compatible area expansion is likely smaller than 50 Mha as simulated here. Moreover, it remains to be analyzed whether these areas are suitable from an economic or social perspective (see Fig. 1 and Supplementary Figs. 9 and 10).

Regardless of the potential strong interference with other dimensions of Earth system stability, the climate benefit of conversion of (semi-)natural vegetation to biomass plantations only plays out with a time lag. Its length depends on the cumulative net carbon balance, which is determined by the local biogeochemical conditions for biomass growth and the previous land cover[43,45,46,59]. In line with the 30-year evaluation timeframe chosen here, biomass plantations were only allocated where their establishment would lead to net CDR within three decades after their establishment. The number of years needed to compensate for potential land use change emissions (carbon payback period, cf.[27,47,59]), however, strongly depends on the previous land cover[43,45–47]. While the first year with net CDR is, on average, reached within 11 years after biomass plantation establishment in the CDRonly scenario (Fig. 4a), the carbon payback period is particularly high in the boreal zone (22 years on average, Fig. 4b) due to a high carbon debt and limited biomass growth. As the suitable areas in the allPBs scenario are primarily located within forested ecosystems, it takes ~14 years to compensate for land use change emissions and reach net CDR in this scenario (Fig. 4a). This time lag underlines that even if PB constraints were disregarded in an effort to

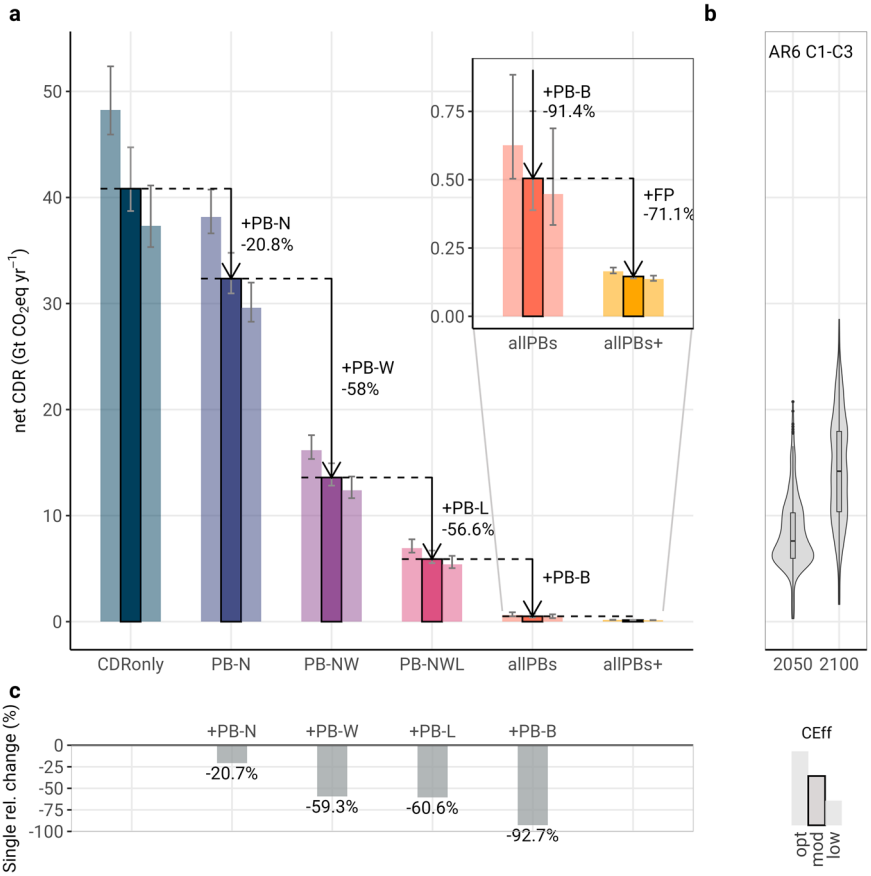

Fig. 3 | Global net carbon dioxide removal from expanding biomass plantations for BECCS under consideration of planetary boundary constraints. **a** Impacts of incremental consideration of planetary boundary (PB) constraints on global BECCS potential. Net carbon dioxide removal (CDR) is displayed for three carbon removal efficiency (CEff) pathways (optimal, moderate, low, assuming a biomass-to-electricity conversion). The error bars reflect the range based on mid-century RCP4.5 climate change scenarios from five general circulation models (2036–2065). Percentage changes refer to the relative incremental effect of each constraint. **b** Projected CDR demand in scenarios likely limiting warming to <2 °C (C1–C3) included in IPCC's 6th assessment report (AR6)[1], boxplots show median and interquartile ranges for 2050 and 2100 respectively (see Supplementary Methods). **c** Single mean effect of the PB constraints relative to the unconstrained CDRonly scenario.

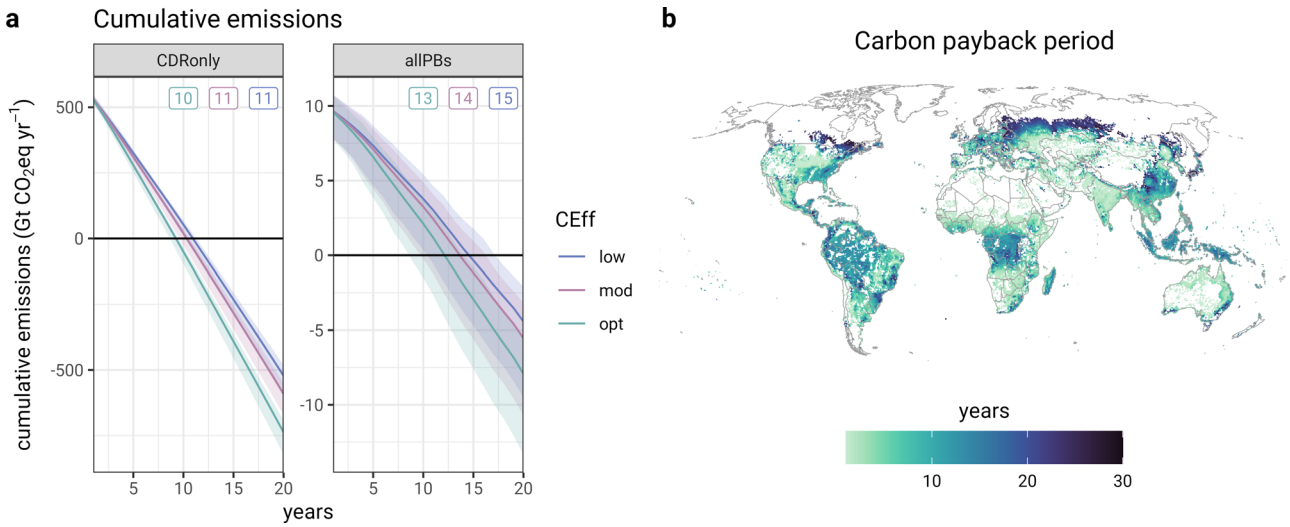

Fig. 4 | Cumulative emissions and carbon payback period. **a** Cumulative emissions for the unconstrained CDRonly scenario and the allPBs scenario, where all terrestrial planetary boundary (PB) constraints are considered. The lines refer to the mean; the shading gives the range for the input from five climate models. The carbon payback period, i.e., the number of years needed to compensate for the initial land use change emissions, is displayed as values in boxes for three carbon removal efficiencies (CEff; low, moderate, optimistic) assuming a biomass-to-electricity conversion. Additional plots for all scenarios can be found in Supplementary Fig. 13. **b** Spatially-explicit carbon payback period under a moderate CEff in the unconstrained CDRonly scenario, averaged for five general circulation models under mid-century RCP4.5 climate.

maximize the BECCS contribution to avoid further transgression of the climate change PB, (i) the short-term benefit of biomass plantation establishment in forested ecosystem seems questionable[45] and (ii) failing to account for these temporal dynamics and/or any delays in deployment may contribute to temperature overshoots. Given that 1.5 °C scenarios without overshoot would require net zero CO_2 emissions in 2050–2055[1], the window is rapidly closing for expanding biomass plantations for BECCS to timely contribute to the Paris climate target (see also ref. 46).

Discussion

This study finds that single PB constraints add up to precluding BECCS from biomass plantations outside of current agricultural areas. Limits to

additional biosphere degradation pose the strongest single constraint, highlighting a particularly strong trade-off between climate change mitigation via BECCS and biosphere protection (yet ultimately all PBs together constrain the overall potential). In the following, we first compare our findings with previous assessments of environmentally constrained BECCS potentials and then discuss uncertainties in our assessment. We subsequently evaluate the limited BECCS potentials in the context of CDR needs projected for climate change mitigation and discuss implications for a broader sustainability transformation of land use.

Limits to plantation-based BECCS under PB constraints

The environmentally "sustainable" potential for plantations-based BECCS outside agricultural areas found here is lower than bioenergy potentials (with or without CCS) estimated in previous studies (2.4 EJ yr^{-1} in the allPBs + scenario in terms of primary energy content vs. 5–149 EJ yr^{-1}[14,24,33–42]). The large range in previous estimates reflects differences in the comprehensiveness of the assumed environmental constraints (see Supplementary Table S11). Importantly, none of the studies have based their analysis on process-based biogeochemical modeling of the impacts on biosphere integrity and nitrogen flows. Instead, most studies excluded areas using external datasets, such as wilderness or water-scarce areas. As forests are excluded in most analyses, converted areas in other studies focus on grassland, shrubland, and savannas, some of which may be considered "marginal"[60]. However, natural grassland and shrubland biomes are often characterized by high biodiversity[61,62], and even rainfed and unfertilized plantations are largely not compatible with PB constraints in these areas in the allPBs scenario. Converting non-forest areas to rainfed/unfertilized biomass plantations would result in widespread increases in pressures on 1–3 terrestrial PBs as shown in an additional analysis (Supplementary Fig. S16). Also, except for Heck et al.[14], no study had considered all terrestrial PB dimensions, with limits to nitrogen pollution, being particularly often omitted (see Supplementary Table S11). This emphasizes the importance of considering all dimensions of Earth system stability for the assessment of nature-compatible CDR potentials, as it is the combination of constraints that ultimately limits the overall potential. The results enhance those of Heck et al.[14] who worked with earlier PB definitions and considered the nitrogen and biosphere integrity PBs only as an exogenous input to the modeling, thus omitting interactive effects. In contrast, we here simulate all terrestrial PBs and the impacts of biomass plantations in one consistent modeling framework and disentangle the contribution of individual PB constraints and their combined effects.

The simulated PB-constrained potentials depend on sufficient accuracy of LPJmL in representing relevant Earth system processes. While considerable uncertainties are inherent to global modeling of the biosphere, the status of simulated PBs and PB-related variables under the current climate align well with findings in the literature (see Supplementary Table 4). Nonetheless, the spatial patterns of PB transgressions are subject to remaining uncertainties at a regional level. For example, Richardson et al.[30] find that the land system change PB is not only transgressed in tropical biomes, as in our assessment, but also in two temperate and boreal biomes. This is due to their use of a satellite-derived data set and different definitions of what constitutes a forest. A greater transgression of the land system change PB due to agriculture would reduce the remaining opportunity spaces for PB-compatible biomass plantations and thus increase the single effect of the land system change PB. However, we account for such uncertainty in the status of the land system change PB in the allPBs+ scenario, where deforestation for biomass plantations is precluded everywhere.

The status of terrestrial PBs is not only impacted by land use but also by climate change[63–65]. In addition to transgressions caused by agriculture, we, therefore, also accounted for the impacts of ~2 °C warming when evaluating constraints on biomass plantation expansion and management. Future studies should advance analysis by exploring the related uncertainties in PB status as a function of future global warming levels and the response of interrelated PB control variables (e.g., nitrogen leaching and river discharge). Should humanity be successful in limiting global warming to well below 2 °C, the nitrogen and freshwater PB constraints on BECCS would likely be less strict, as climate change-induced transgressions could be prevented, expanding remaining opportunity spaces for BECCS. This points to an important trade-off: While large-scale plantation-based BECCS would contribute to preventing climate change-induced PB transgressions, it would at the same time severely increase land use-related PB transgressions, potentially even more than offsetting the prevented effects from climate change[18,19,22]. This stresses the importance of climate change mitigation as the foremost strategy, including rapid decarbonization and a portfolio of lower-impact CDR options.

Already now, all four terrestrial PBs are transgressed at the global level[30]. In a strict sense, any expansion of land use would, therefore, put additional pressure on these PBs. Given the particular importance of the climate change PB for Earth system stability, defined as a "core boundary"[30], we here, however, focused on spatially explicit regional definitions to assess regionally safe opportunity spaces for BECCS. The results depend on these regionally defined PB constraints. Their definitions, however, should at present still be considered "work-in-progress" as they are subject to ongoing debate and improvement (e.g., Wang-Erlandsson et al.[66], Richardson et al.[30], and Porkka et al.[67] for the freshwater PB).

Given the particularly strong effect of the PB constraint addressing biosphere integrity, we additionally tested the effect of a different, empirically derived, biosphere integrity metric (see Supplementary Methods): The Biodiversity Intactness Index (BII), which had been previously proposed as a provisional control variable for this PB[29,68]. While the single constraint would be less strict, albeit still the strongest among the four terrestrial PBs (75% reduction compared to the CDRonly scenario), the overall results regarding the cumulative effect of all four PBs in the allPBs+ scenario is only marginally affected (0 $GtCO_2eq\ yr^{-1}$ instead of 0.1 $GtCO_2eq\ yr^{-1}$; see Supplementary Fig. 15 and Supplementary Table 8). Moreover, we applied the constraint on biosphere degradation on the level of biomes, as the geographical entities relevant for planetary-scale impacts on biosphere integrity[69]. Testing the effect of applying the constraint at the more disaggregated level of ecoregions instead[70] would still not allow for more than 1 $GtCO_2eq\ yr^{-1}$ in the allPBs+ scenario (see Supplementary Fig. 15 and Supplementary Table 8). Future research may contribute to a better understanding of the most suitable scale for assessing the trade-off between climate change mitigation and biosphere integrity. Further, we focused on the functional component of the biosphere integrity PB to represent the biosphere's capacity to sustain functional feedbacks within the Earth system[30]. As LPJmL does not represent species richness, it was not possible to additionally account for genetic diversity, the second and already severely transgressed component of the biosphere integrity PB[29,30]. Yet, previous global-scale studies have shown that expansion of biomass plantations would entail stark impacts on species richness and increase extinction rates, depending on the modeling assumptions even surpassing the prevented effects from climate change on biodiversity[18,19]. Regardless of the control variable and scale of assessment, preventing further biosphere degradation is here shown to be a key limiting factor for plantation-based BECCS, in line with previous assessments[41,71]. It has been argued that biosphere integrity, next to climate change, is one of the two core PBs, due to their strong interaction with other boundaries[29]. Substantial shifts in both climate and the biosphere have strongly altered the state of the Earth system in the past and are capable of pushing Earth out of its Holocene state[30]. Despite uncertainties in the assessment and definition of limits to biosphere degradation that safeguard Earth system stability, combatting climate change at the cost of biosphere integrity is no scientifically well-founded strategy[72].

Simulation of net CDR

In this study, we calculated net BECCS potentials based on process-based modeling of management-dependent yields on biomass plantations and land use change emissions as well as supply chain emissions for three different CDR efficiencies. While we focused on CO_2 removal, we additionally tested the inclusion of N_2O emissions as an additional contribution to the

overall net greenhouse gas removal efficiency. This, however, only marginally impacts the results (see Supplementary Fig. 14). It is important to note that simulated absolute net CDR potentials and carbon payback times are highly uncertain[47]. If current or assumed future yield gaps were accounted for[46], instead of referring to (well-validated, see Supplementary Figs. 2 and 3) biophysical yields, absolute CDR potentials would decrease. On the other hand, yearly potentials would increase with (i) a longer evaluation timeframe than the here assumed 30 years[46], (ii) assuming locally optimal crops, e.g., short rotation coppice might have higher yields than Miscanthus in some locations[73], and (iii) assuming the cleared biomass upon plantation establishment to be used as feedstock for BECCS (instead of assuming its emission)[42,45,46]. Overall, the here simulated net CDR potentials per area in the unconstrained CDRonly scenario are lower than in Heck et al.[14] for the similarly efficient biomass-to-hydrogen conversion, but higher than in Hanssen et al.[46] referring to the same evaluation period and biomass-to-electricity conversion but accounting for potential yield gaps. While this study focuses on net CDR from BECCS aimed at limiting or reversing the climate change PB transgression, further studies have assessed the broader climate mitigation effects of BECCS, including fossil fuel substitution[42,74], which is a key advantage of BECCS over other CDR methods[75,76]. Here, the aim is to evaluate the relative constraining effect of terrestrial PBs on BECCS rather than to explore a range of deployment pathways. In terms of the energy conversion, we assumed the highly efficient biomass-to-electricity pathway in line with our optimization approach to assess the maximum BECCS potential (see Supplementary Table S10 for primary energy and electricity potentials). However, BECCS will likely partially be deployed based on much less efficient biomass-to-liquid pathways to substitute fossil fuels in transport, which would (i) reduce simulated BECCS potentials and (ii) increase the carbon payback period[27,46], thus further questioning the timely benefit to the climate change PB in many regions, irrespective of terrestrial PBs.

Sustainable BECCS potentials for climate change mitigation

We here show that terrestrial PBs strongly limit the responsible expansion options for biomass plantations—be it for BECCS or mere bioenergy production—even further than estimated in previous studies that did not account for all terrestrial PB dimensions. This emphasizes that environmental constraints and associated risks addressing all terrestrial PB domains, particularly biosphere integrity, need to be comprehensively accounted for in future pathways for sustainable development. This implies accounting for process-based and spatially explicit impacts on terrestrial and aquatic ecosystems and considering matters of overall Earth system stability. While delays in stringent decarbonization are projected to significantly increase the need for CDR[1,77,78], climate stabilization scenarios that specifically follow a broader sustainable development pathway are characterized by substantially lower CDR demand[79–81]. These scenarios represent strategies of rigorously reducing emissions and pursuing comprehensive socioeconomic transformations (including environmental constraints), therefore, providing evidence that the Paris climate limits are reachable without strong expansion of biomass plantations for BECCS[79–81]. This emphasizes the normative component of the magnitude of overshoot and residual "hard-to-abate" emissions that would need to be compensated by CDR, which is co-shaped not just by economic and technological considerations but also societal values, norms, and interests[8,27,82–84]. The findings of this study regarding PB-constrained BECCS potentials are also in line with studies showing that a broader portfolio of CDR technologies and practices can decrease the dependence on BECCS and increase the "low risk" potentials overall[85–87].

With regard to the supply side, i.e., how much BECCS could be sustainably provided for climate change mitigation, it is important to consider that we here analyzed systematic scenarios, focusing on biogeochemical potentials under PB constraints. Real-world potentials would encounter additional socioeconomic constraints, which would likely further reduce the CDR potential[38]. For example, the remaining areas in the allPBs scenario could be not suitable or their conversion desirable with regard to other sustainability and/or feasibility considerations[19,38,88]. Also, this study focused on plantation-based BECCS given the potential severe trade-offs with terrestrial PBs. However, previous studies showed that there may be some, albeit limited, "sustainable" BECCS potentials without expanding biomass plantations: (i) current (first-generation) bioenergy crop plantations (ca. 50 Mha) which may contribute to BECCS at least without adding further pressures on terrestrial PBs[16,27] and (ii) agricultural and forestry residues[10,34,89,90], or biogenic point sources e.g., from pulp and paper industries or municipal solid waste[91,92]. While these feedstocks can provide substantial sustainability advantages, particularly because of the avoided land competition with food and nature, (i) the feedstock availability is uncertain and limited[1,10,27] and (ii) residues and waste cannot be considered freely available in the light of competing uses or benefits[34,89]. The same applies to selective logging of managed forests for BECCS, which, while potentially having less severe impacts on PBs[93], stands in competition with future material demand[38] and is simulated to contribute little to CDR in integrated assessment models[94].

Similarly, sustainable crop-based BECCS potentials strongly depend on land and resources needed for other purposes. We here assumed reserving current agricultural areas for provision of food, fodder and fiber for a growing world population. However, if agricultural resource demand further increases in the future, regional opportunities for PB-constrained BECCS plantations could further shrink (e.g., if nitrogen inputs and irrigation for food production increased in the Global South, thus increasing food-related pressures on PBs). On the other hand, technological advances and comprehensive sustainability transformations in the food system could increase PB-constrained BECCS potentials: While current trends point to the opposite[95], diet changes towards fewer animal products in wealthy nations would not only benefit health[96], but dually contribute to climate change mitigation: (i) by reducing residual emissions (primarily methane) and thus CDR demand and (ii) by freeing up land areas for CDR, particularly pastures[80,97–99]. While previous studies have pointed to high BECCS potentials on spared agricultural land[34,100], it is crucial to thoroughly assess PB impacts of such land conversions in future studies, considering also the importance of reverting current PB transgressions through a sustainability transformation of anthropogenic land use[31]. Also, CDR potentials on such lands need to be thoroughly assessed, considering alternative uses such as natural revegetation[34,42]. Such assessments should account for land use history and potential soil degradation for simulation of (potentially reduced) biomass yields[39,101] in comparison to plantation establishment on (semi-) natural land as simulated in this study.

Conclusions

Based on spatially explicit and process-based simulation of terrestrial PB transgressions, our analysis shows that PB constraints collectively limit plantation-based BECCS potentials to close to zero if current agricultural areas are safeguarded. While the effect of individual PB constraints on the expansion and management of biomass plantations varies in strength and spatial distribution, the results indicate that conversion of (semi-)natural vegetation to biomass plantations is highly problematic if CDR provision is not to undermine other aspects of Earth system stability. Overall, the findings stress the necessity for rapid decarbonization as the only way to not burden future generations with highly undesirable trade-offs between climate stabilization and safeguarding terrestrial PBs.

Methods

To calculate the maximum BECCS potential under PB constraints, we optimize the spatial distribution of biomass plantations while preventing further transgressions of single or multiple PBs and preserving agricultural, urban, and protected areas as well as wetlands. The spatially detailed biophysical and biogeochemical constraints required for the optimization, as well as the resulting optimized land use patterns, are simulated with the global biosphere model LPJmL. In the following, we describe (i) key LPJmL processes and the simulation protocol and (ii) the BECCS optimization scenarios with details on the optimization target and the calculation of net

CDR as well as the definition of PB constraints for nitrogen flows, freshwater change, land system change, and biosphere integrity.

The global biosphere model LPJmL

The LPJmL model (version 5.8.5)[102] dynamically simulates both natural and agricultural vegetation based on spatially explicit and process-based modeling of interconnected water, carbon (C), and nitrogen (N) fluxes, at daily timesteps and $0.5° \times 0.5°$ spatial resolution. Natural vegetation is represented by eleven plant functional types with dynamic distribution as a result of competition for light, water, and nutrients. Anthropogenic land use is prescribed by datasets of historic patterns and future scenarios, including the grid cell-specific extent of irrigated and rainfed areas for 12 crop functional types and managed grassland[103]. Agricultural management intensity can further be prescribed by application rates of manure and mineral fertilizer, amongst others. To represent second-generation energy crops as feedstocks for BECCS, biomass plantations with lignocellulosic C4 grass (biograss) are parametrized based on observations for *Miscanthus*[39,104,105]. For robust representation of management-dependent processes and environmental impacts on biomass plantations, LPJmL5 was here enhanced by (i) defining N-related biograss parameters based on literature and the corresponding natural plant functional types in LPJmL, as previous biograss implementations were based on a model version without N dynamics and (ii) implementing cell-specific fertilization on biomass plantations (see Supplementary Methods for details and evaluation).

As particularly the nitrogen and freshwater PB constraints (see below) depend on a robust representation of agricultural management impacts on water and N dynamics, we provide details on the respective key processes simulated in LPJmL in the following (for detailed model descriptions and validations of LPJmL's biogeochemical dynamics see Schaphoff et al.[50], Schaphoff et al.[106] and von Bloh et al.[51]). For irrigation, plant type-specific water demand is computed based on the soil water deficit and is requested for withdrawal from local renewable freshwater resources, taking into account the system-specific inefficiencies of surface, sprinkler or drip irrigation[107]. For simulation of river discharge, surface and subsurface runoff accumulate along the river network, with respective reductions through computed withdrawals for irrigation and prescribed withdrawals for households, industry and livestock. With regard to N dynamics on agricultural land, soil N pools receive input from dynamically modeled decomposition of plant biomass and biological N fixation as well as prescribed atmospheric deposition and scenario-specific fertilization. The amount of fertilization thereby impacts the process-based soil N transformations, plant N uptake and productivity as well as N losses. The latter comprises N losses to the atmosphere and nitrate losses in runoff to renewable freshwater resources.

Simulation protocol

Using LPJmL, we simulated all spatially explicit inputs for mid-century RCP4.5 climate (2036–2065) needed for the optimization model: (i) the status of PBs and related variables in the agricultural baseline scenario (current agricultural areas without expansion of biomass plantations), and (ii) potential impacts on PB statuses as well as changes in C pools (vegetation, litter, soil) and yields following from assumed expansion of biomass plantations. Preceding all simulations, an equilibrium of the distribution of natural vegetation as well as C and N stocks was achieved by recycling the 1850–1879 climate[54] in a 3500-year spin-up. Transient historical land use from 1500 to 2017 then accounted for the influence of agriculture on the C, N, and water cycle, differentiating irrigated and rainfed areas and considering crop-specific fertilizer and manure applications[108] (for a complete list of used input data see Supplementary Table 1). For the subsequent simulation of the optimization inputs under mid-century climate with ~2° of warming, MRI-ESM-2.0[109] was chosen as a climate model with moderate climate sensitivity, projecting a mean global warming of 2 °C in 2050 under RCP4.5 forcing and SSP2 socioeconomic development in line with the CMIP6 mean for 2041–2060[1,54]. In line with our assumption to reserve current agricultural areas for food, fodder, and fiber, the land use pattern and management for 2017 was held constant until 2065 for the agricultural baseline scenario, as well as for scenarios with additional biomass plantations (see below). To simulate changes in C pools, runoff, and N leaching as well as potential yields from converting (semi-)natural areas into biomass plantations, four potential management options on those plantations were simulated: rainfed (rf) and irrigated (irr), each with either optimal or no fertilizer application, respectively (Fert, noFert). Cell-specific optimal fertilization levels, separated for rainfed and irrigated conditions, were derived from simulated harvested N under unlimited N supply, thus considering the strong dependence of fertilizer requirements on spatially explicit soil properties, water availability, and climate conditions (for an overview of the simulation setup and all performed simulations and their purposes and details on the fertilizer calculation, see Supplementary Methods). All land use patterns generated by the optimization model (i.e., areas with biomass plantations outside agricultural areas, and their management; under individual or joint PB constraints) were simulated with LPJmL under 2036–2065 SSP2–4.5 climate applying climate inputs from the five CMIP6 models included in ISIMIP3b[54,110–113] to account for uncertainty regarding net CDR potentials depending on the climate forcing. For configuration of all simulations and reading of LPJmL outputs, the R package lpjmlkit was used[114,115].

BECCS optimization scenarios

To derive maximum plantation-based BECCS potentials constrained by PBs, we (i) defined the areas potentially available for biomass plantations and (ii) optimized the geographic distribution of plantations in these areas to maximize CDR under PB constraints. For (i), we excluded all 2017 agricultural[108] and 2015 urban areas[116], thus only allowing for the conversion of (semi-)natural vegetation to biomass plantations. Further, we blocked all protected areas according to IUCN&UNEP-WCMC[117] and wetlands from Lehner and Döll[118], given the counteractive climate effect of draining wetlands. To only consider cells with economically reasonable yields on biomass plantations, we applied a minimum yield threshold of 5 t DM ha^{-1} yr^{-1}[19] (see Supplementary Figs. 4 and 5 for simulated potential biomass yields and excluded areas). The remaining areas thus include (unprotected) natural forests, shrubland and grassland (parts of which may be considered marginal), and managed forests.

We refined and expanded the optimization model developed by Heck et al.[14]: First, we calculated the potential net CDR for each grid cell ($j = 1 \ldots n$) and biomass plantation management option ($p \in \{rf_Fert, rf_noFert, irr_Fert, irr_noFert\}$) by multiplying the 30-year harvest from biomass plantations (H_j^p) with a carbon removal efficiency ($CEff$) and subtracting land use change emissions (LUC_j^p):

$$netCDR_j^p = H_j^p * CEff - LUC_j^p \quad (1)$$

H and LUC were obtained from global LPJmL simulations of biomass plantations with fertilization levels and/or irrigation as described above. LUC through the expansion of biomass plantations was calculated based on the difference in C pools (soil, litter, vegetation) between biomass plantations and natural vegetation 30 years after establishment. Similar to previous LPJmL-based studies[14,43,46], LUC thereby includes initial land use change emissions due to land clearing as well as gradual changes in soil and litter carbon pools[43]. By comparing C pools on biomass plantations to the counterfactual case of continued natural vegetation under the same climate, the potential "lost sequestration capacity" in the natural vegetation due to CO_2 fertilization amongst others, is also considered[46]. Timber harvest upon clearing of natural vegetation for biomass plantations was presumed to be harvested for wood products[45] and not considered for net CDR, on the assumption that it will ultimately be fully converted into CO_2 ("committed emissions"). For $CEff$, we applied three scenarios for biomass-to-electricity conversion from the MONET framework with a detailed representation of the BECCS supply chain including emissions arising from cultivation, harvest, processing, and transport of biomass, as well as downstream CO_2 emissions associated with the capture, transport, and storage of CO_2 into

geological reservoirs[52] (see Supplementary Methods for an overview on assumptions regarding capture efficiencies, transport distance and carbon footprint of electricity amongst others). This results in a CEff of 84% for the moderate pathway and a range of 80 to 92% for conservative and optimistic assumptions, respectively.

To maximize net CDR under regional PB constraints (C_{PB}^{reg}) of freshwater change (W), nitrogen flows (N), land system change (L), and/or biosphere integrity (B), a linear weighted sum optimization was then performed based on the R package lpSolveAPI[14,120]. The geographic distribution of cell fractions with biomass plantations (f_j^p) and their management was thus optimized as follows:

$$\max_{f_j \in C_{PB}^{reg}} \left(\sum_{j=1}^{n} \sum_{p} f_j^p \cdot netCDR_j^p \right) \quad (2)$$

with the regional constraints C_B^{reg}, C_W^{reg}, C_N^{reg}, and/or C_L^{reg}. In line with the net CDR maximization, biomass plantations are not allocated in areas with resulting positive emissions due to land use and supply chain emissions. As the area within cells can be split between different management options, irrigated/fertilized areas are allocated as far as the respective PB constraint allows for and where net CDR is thereby increased. The remaining area is allocated to rainfed/unfertilized plantations, again, as far as the PB constraints allow. For all scenarios, irrigated and/or fertilized plantations may only be allocated if yields are increased by >10% as compared to rainfed/unfertilized conditions, respectively. Given the non-linear effects of irrigation and fertilization on biomass yields and environmental variables, irrigated and fertilized areas rather than irrigation and fertilization levels (in terms of input per area) are optimized.

Planetary boundary constraints

Land use expansion for biomass plantations and intensified management (irrigation, fertilization) on these is allowed up to the point where regional environmental limits according to the PB framework are reached. All cells where these PB values are already transgressed in the agricultural baseline scenario are excluded for conversion to biomass plantations (see Table 1 for an overview of all regional PB values and the regional resolution of the constraints).

Nitrogen flows. We focus on limits to surface water eutrophication as this is a major concern associated with anthropogenic modifications of the N cycle[29]. Additionally, it has been shown that complying with surface eutrophication thresholds likely also results in acceptable levels of terrestrial eutrophication and groundwater pollution in most regions[121,122]. As suggested by de Vries et al.[122] and Schulte-Uebbing et al.[123], we thus define regional N thresholds based on critical N concentrations in runoff (through surface and subsurface runoff and leaching N flows) from agricultural and natural land to surface waters as dynamically simulated by LPJmL. Based on the ecological and toxicological effects of inorganic N pollution, 1 mgN l^{-1} has been suggested as precautionary boundary for inorganic N concentration in surface waters[124–126]. Assuming that on average 50% of N flowing into surface waters is retained or sedimented[123], the maximum PB-compatible N concentration in runoff is set to 2 mgN l^{-1}. By defining limits to N in runoff, we capture potential transgressions in all tributary streams and argue that, if thresholds in runoff are complied with, any downstream transgression would also be prevented. Our approach focuses on the agricultural impact on surface water eutrophication by considering N losses from soils, exclusively. As in Chang et al.[121] and de Vries et al.[122], additional N inputs to surface waters from direct atmospheric deposition and point sources such as sewage or aquaculture are not accounted for.

For the optimization constraint C_N^{reg}, biomass plantations can be allocated to cells until the maximum N concentration in runoff according to the PB definition ($PB_{threshold}$) is reached. The maximum allowable additional N load in runoff from biomass plantations (N budget) is calculated for each cell j as follows, based on the yearly runoff ($runoff_{agr}$) and N load within runoff (N_{agr}) in the agricultural baseline scenario under 2036–2065 climate:

$$Nbudget_j = runoff_{agr_j} \cdot PB_{threshold} - N_{agr_j}, set\ to\ 0\ if < 0 \quad (3)$$

In cells with arid climate ($\frac{annual\ precipitation}{potential\ evapotranspiration} < 0.2$[127]), the constraint is not applied due to negligible leaching[128]. Total added N load from all biomass plantation types within a cell j must be smaller than the remaining $N\ budget_j$, so that combined N loads from the agricultural baseline and biomass plantations do not transgress the regional threshold for runoff.

Freshwater change. While diverse approaches for the freshwater PB are currently being discussed[66,129,130], we use the sub-global control variable for freshwater use defined in Steffen et al.[29], which refers to the minimum river flow required to maintain at least a "fair" ecological status within rivers. These environmental flows were here determined for each grid cell based on the variable monthly flow method and preindustrial climate for 1851–1880[29,131] (for flow regime dependent classification and thresholds for river flow reductions, see Table 1). For the freshwater constraint, we calculated the available monthly water for biomass plantations (W_{avail}) for each cell j by subtracting environmental flows from simulated discharge in the agricultural baseline for each month (set to 0 if <0, i.e., if environmental flows are already transgressed through agriculture and/or climate change). Within the optimization, biomass plantations (rainfed or irrigated, with or without fertilization) may only be added as long as resulting river flow changes (from irrigation and/or changes in runoff on plantations, FlowChanges) do not lead to additional PB transgressions in any month of the year. The constraint takes effect at the cell level and, to account for upstream-downstream effects, upstream flow changes are considered for all downstream cells:

$$\sum_{uc} \sum_{p} (FlowChanges_{uc}^{p}) \le W_{availj} \quad (4)$$

$$with\ uc = cell\ j\ and\ all\ its\ upstream\ cells$$

$$p \in \{rf_Fert, rf_noFert, irr_Fert, irr_noFert\}, covering\ partial\ shares\ of\ cell\ j$$

In the absence of the freshwater constraint, river flow reductions from biomass plantations are only allowed to the extent of monthly available discharge in the agricultural baseline, i.e., if irrigation requirements can always be fulfilled throughout the year. With and without the constraint, irrigation of biomass plantations is only assumed if yields are increased at least by 10%.

Land system change. As proposed in Steffen et al.[29] and Richardson et al.[30], biome-specific limits to land system change were defined based on remaining forest cover to acknowledge the importance of forests in climate regulation (see Table 1 with biome-specific thresholds). Potential forest extent was defined based on Dinerstein et al.[70], aggregated to 0.5° resolution, and distinguishing tropical, temperate, and boreal forest biomes. For "Mediterranean Forests, Woodlands & Scrub", the only biome not clearly classified as forest, we only included cells with >60% tree cover simulated with LPJmL (see Supplementary Fig. 7 for a map with forest biomes). The remaining tropical, temperate, and boreal forest cover for each of the 7 biogeographic realms[70] was then determined by subtracting pasture and cropland areas from potential forest cover. For biome-specific land system change constraints in the optimization, conversion of forests to biomass plantations is only allowed to the extent that deforestation from both agricultural areas and biomass plantations does not exceed the biome-level boundaries.

Biosphere integrity. Net primary productivity (NPP) and the associated photosynthetic energy and material flows are crucial for maintaining the

planetary ecological functions of biomes. Richardson et al.[30] therefore suggested BioCol, the human appropriation of net primary productivity (NPP) as a fraction of the biosphere's Holocene NPP, as a computable control variable for the functional component of the biosphere integrity PB, with 10% as a precautionary PB (see Table 1). Following Stenzel et al.[57], we simulate BioCol based on process-based modeling of (i) extraction of biomass and (ii) prevention of natural NPP due to land use change and management. For (i), extracted C from cropland (incl. residues) and managed grassland is included, and—for scenarios of biomass plantation expansion—timber removal upon land use expansion as well as harvest on biomass plantations. In the absence of a calibrated managed forest module in LPJmL5, we combine this with external data on timber harvest from LUH2-v2h[116], keeping the latest available data from 2014 constant until 2017. For (ii), we compare the respective land use scenario to a scenario with potential natural vegetation, i.e., free of human land use, both under the same climate conditions and thereby account for land use-related decreases in NPP. The thereby simulated human appropriation of NPP is translated into a relative fraction of Holocene NPP based on simulated NPP under potential natural vegetation and pre-industrial climate (1851–1880), as suggested in Richardson et al.[30]. For biome-specific limits to biosphere degradation, BioCol is computed for each biome within each of 7 biogeographic realms[70] based on the biospheremetrics R package[132]. Biomass plantations are restricted to biomes where agricultural BioCol is <10%, and must not lead to exceeding this limit, i.e., natural vegetation can be converted to biomass plantations as long as BioCol would remain ≤10%.

Calculation of carbon payback periods

For calculating the carbon payback period for each grid cell where biomass plantations expanded into (semi-)natural vegetation, the cell-specific net CDR potential was calculated for each year of the 30-year evaluation period, taking into account cumulative harvest until the respective year, as well as simulated land use change emissions up to that year. By identifying the first year with net negative emissions through BECCS (i.e., when land use change emissions are compensated by cumulative harvest, subtracting BECCS supply chain emissions), the carbon payback period is determined.

Data availability

The data generated in this study, including source data for all figures, are publicly available under the Creative Commons Attribution 4.0 International license at Zenodo [133].

Code availability

The model code for LPJmL (version 5.8.5) used in this study, and the corresponding R scripts for the analysis and creation of the figures are publicly available under the Creative Commons Attribution 4.0 International license at Zenodo [133].

Received: 31 May 2024; Accepted: 14 January 2025;
Published online: 12 February 2025

References

1. IPCC. *Climate Change 2022. Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2022).
2. Fuss, S. et al. Betting on negative emissions. *Nat. Clim. Change* **4**, 850 (2014).
3. Galik, C. S. A continuing need to revisit BECCS and its potential. *Nat. Clim. Change* **10**, 2–3 (2020).
4. Low, S. & Schäfer, S. Is bio-energy carbon capture and storage (BECCS) feasible? The contested authority of integrated assessment modeling. *Energy Res. Soc. Sci.* **60**, 101326 (2020).
5. Smith, S. M. et al. *The State of Carbon Dioxide Removal*—1st Edition. (2023).
6. Forster, J., Vaughan, N. E., Gough, C., Lorenzoni, I. & Chilvers, J. Mapping feasibilities of greenhouse gas removal: Key issues, gaps and opening up assessments. *Glob. Environ. Change* **63**, 102073 (2020).
7. Brack, D. & King, R. Managing land-based CDR: BECCS, forests and carbon sequestration. *Glob. Policy* **12**, 45–56 (2021).
8. Schleussner, C.-F. et al. Overconfidence in climate overshoot. *Nature* **634**, 366–373 (2024).
9. Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W. & Clarens, A. F. From Zero to Hero?: Why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Front. Clim.* https://doi.org/10.3389/fclim.2019.00011 (2019).
10. Hanssen, S. V. et al. Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models. *Clim. Change* **163**, 1569–1586 (2020).
11. Byers, E. et al. AR6 Scenarios Database. *Zenodo*. https://doi.org/10.5281/zenodo.7197970 (2022).
12. FAO. *FAOSTAT—Land, Inputs and Sustainability/Land Use*. (2024).
13. Humpenöder, F. et al. Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environ. Res. Lett.* **13**, 024011 (2018).
14. Heck, V., Gerten, D., Lucht, W. & Popp, A. Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat. Clim. Change* **8**, 151–155 (2018).
15. Creutzig, F. et al. Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* **7**, 916–944 (2015).
16. Creutzig, F. et al. Considering sustainability thresholds for BECCS in IPCC and biodiversity assessments. *GCB Bioenergy* **13**, 510–515 (2021).
17. IPCC. *Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* (eds P. R. Shukla et al.) (2019).
18. Hof, C. et al. Bioenergy cropland expansion may offset positive effects of climate change mitigation for global vertebrate diversity. *Proc. Natl Acad. Sci. USA* **115**, 13294–13299 (2018).
19. Hanssen, S. V. et al. Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity. *GCB Bioenergy* **14**, 307–321 (2022).
20. Stoy, P. C. et al. Opportunities and Trade-offs among BECCS and the Food, Water, Energy, Biodiversity, and Social Systems Nexus at Regional Scales. *BioScience* **68**, 100–111 (2018).
21. Stenzel, F., Gerten, D. & Hanasaki, N. Global scenarios of irrigation water abstractions for bioenergy production: a systematic review. *Hydrol. Earth Syst. Sci.* **25**, 1711–1726 (2021).
22. Stenzel, F. et al. Irrigation of biomass plantations may globally increase water stress more than climate change. *Nat. Commun.* **12**, 1512 (2021).
23. Li, W. et al. Bioenergy crops for low warming targets require half of the present agricultural fertilizer use. *Environ. Sci. Technol.* **55**, 10654–10661 (2021).
24. Ai, Z., Hanasaki, N., Heck, V., Hasegawa, T. & Fujimori, S. Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation. *Nat. Sustain.* **4**, 884–891 (2021).
25. Bonsch, M. et al. Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy* **8**, 11–24 (2016).
26. Boysen, L. R., Lucht, W. & Gerten, D. Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Glob. Change Biol.* **23**, 4303–4317 (2017).
27. Deprez, A. et al. Sustainability limits needed for CO2 removal. *Science* **383**, 484–486 (2024).
28. Rockström, J. et al. A safe operating space for humanity. *Nature* **461**, 472–475 (2009).

29. Steffen, W. et al. Planetary boundaries: guiding human development on a changing planet. *Science* **347**, 1259855 (2015).
30. Richardson, K. et al. Earth beyond six of nine planetary boundaries. *Sci. Adv.* **9**, eadh2458 (2023).
31. Gerten, D. et al. Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nat. Sustain.* **3**, 200–208 (2020).
32. Campbell, B. M. et al. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society* **22** https://doi.org/10.5751/ES-09595-220408 (2017).
33. Næss, J. S., Cavalett, O. & Cherubini, F. The land–energy–water nexus of global bioenergy potentials from abandoned cropland. *Nat. Sustainability* **4**, 525–536 (2021).
34. Kalt, G. et al. Greenhouse gas implications of mobilizing agricultural biomass for energy: a reassessment of global potentials in 2050 under different food-system pathways. *Environ. Res. Lett.* **15**, 034066 (2020).
35. Erb, K.-H., Haberl, H. & Plutzar, C. Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy* **47**, 260–269 (2012).
36. WBGU. *Future Bioenergy and Sustainable Land Use*. (2009).
37. van Vuuren, D. P., van Vliet, J. & Stehfest, E. Future bio-energy potential under various natural constraints. *Energy Policy* **37**, 4220–4230 (2009).
38. Searle, S. & Malins, C. A reassessment of global bioenergy potential in 2050. *GCB Bioenergy* **7**, 328–336 (2015).
39. Beringer, T., Lucht, W. & Schaphoff, S. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy* **3**, 299–312 (2011).
40. Schueler, V., Fuss, S., Steckel, J. C., Weddige, U. & Beringer, T. Productivity ranges of sustainable biomass potentials from non-agricultural land. *Environ. Res. Lett.* **11**, 074026 (2016).
41. Wu, W. et al. Global advanced bioenergy potential under environmental protection policies and societal transformation measures. *GCB Bioenergy* **11**, 1041–1055 (2019).
42. Gvein, M. H. et al. Potential of land-based climate change mitigation strategies on abandoned cropland. *Commun. Earth Environ.* **4**, 39 (2023).
43. Daioglou, V. et al. Greenhouse gas emission curves for advanced biofuel supply chains. *Nat. Clim. Change* **7**, 920–924 (2017).
44. Fargione, J., Hill, J., Tilman, D., Polasky, S. & Hawthorne, P. Land clearing and the biofuel carbon debt. *Science* **319**, 1235–1238 (2008).
45. Harper, A. B. et al. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nat. Commun.* **9**, 2938 (2018).
46. Hanssen, S. V. et al. The climate change mitigation potential of bioenergy with carbon capture and storage. *Nat. Clim. Change* **10**, 1023–1029 (2020).
47. Fajardy, M. & Mac Dowell, N. Can BECCS deliver sustainable and resource efficient negative emissions? *Energy Environ. Sci.* **10**, 1389–1426 (2017).
48. UN. *World Population Prospects 2022: Summary of Results* (United Nations Department of Economic and Social Affairs). Report No. UN DESA/POP/2022/TR/NO. 3 (2022).
49. Foley, J. A. et al. Solutions for a cultivated planet. *Nature* **478**, 337–342 (2011).
50. Schaphoff, S. et al. LPJmL4—a dynamic global vegetation model with managed land—Part 1: model description. *Geosci. Model Dev.* **11**, 1343–1375 (2018).
51. von Bloh, W. et al. Implementing the nitrogen cycle into the dynamic global vegetation, hydrology, and crop growth model LPJmL (version 5.0). *Geosci. Model Dev.* **11**, 2789–2812 (2018).
52. Chiquier, S., Patrizio, P., Bui, M., Sunny, N. & Mac Dowell, N. A comparative analysis of the efficiency, timing, and permanence of CO2 removal pathways. *Energy Environ. Sci.* **15**, 4389–4403 (2022).
53. Fajardy, M., Chiquier, S. & Mac Dowell, N. Investigating the BECCS resource nexus: delivering sustainable negative emissions. *Energy Environ. Sci.* **11**, 3408–3430 (2018).
54. Lange, S. & Büchner, M. ISIMIP3b bias-adjusted atmospheric climate input data (v1.1). *ISIMIP Repository*. https://doi.org/10.48364/ISIMIP.842396.1 (2021).
55. Cadoux, S., Riche, A. B., Yates, N. E. & Machet, J.-M. Nutrient requirements of Miscanthus x giganteus: Conclusions from a review of published studies. *Biomass Bioenergy* **38**, 14–22 (2012).
56. Chen, H. et al. Influences of nitrogen fertilization and climate regime on the above-ground biomass yields of miscanthus and switchgrass: a meta-analysis. *Renew. Sustain. Energy Rev.* **108**, 303–311 (2019).
57. Stenzel, F. et al. Biospheremetrics v1.0.2: an R package to calculate two complementary terrestrial biosphere integrity indicators—human colonization of the biosphere (BioCol) and risk of ecosystem destabilization (EcoRisk). *Geosci. Model Dev.* **17**, 3235–3258 (2024).
58. Gidden, M. J. et al. Aligning climate scenarios to emissions inventories shifts global benchmarks. *Nature* **624**, 102–108 (2023).
59. Elshout, P. M. F. et al. Greenhouse-gas payback times for crop-based biofuels. *Nat. Clim. Change* **5**, 604–610 (2015).
60. Cai, X. M., Zhang, X. A. & Wang, D. B. Land availability for biofuel production. *Environ. Sci. Technol.* **45**, 334–339 (2011).
61. Murphy, B. P., Andersen, A. N. & Parr, C. L. The underestimated biodiversity of tropical grassy biomes. *Philos. Trans. R. Soc. B:- Biol. Sci.* **371**, 20150319 (2016).
62. Searchinger, T. D. et al. High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. *Nat. Clim. Change* **5**, 481–486 (2015).
63. Gerten, D. & Kummu, M. Feeding the world in a narrowing safe operating space. *One Earth* **4**, 1193–1196 (2021).
64. Lade, S. J. et al. Human impacts on planetary boundaries amplified by Earth system interactions. *Nat. Sustain.* **3**, 119–128 (2020).
65. Tobian, A. et al. Climate change critically affects the status of the land-system change planetary boundary. *Environ. Res. Lett.* **19**, 054060 (2024).
66. Wang-Erlandsson, L. et al. A planetary boundary for green water. *Nat. Rev. Earth Environ.* **3**, 380–392 (2022).
67. Porkka, M. et al. Notable shifts beyond pre-industrial streamflow and soil moisture conditions transgress the planetary boundary for freshwater change. *Nat. Water* **2**, 262–273 (2024).
68. Newbold, T. et al. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* **353**, 288–291 (2016).
69. Mace, G. M. et al. Approaches to defining a planetary boundary for biodiversity. *Glob. Environ. Change* **28**, 289–297 (2014).
70. Dinerstein, E. et al. An ecoregion-based approach to protecting half the terrestrial realm. *BioScience* **67**, 534–545 (2017).
71. Frank, S. et al. Land-based climate change mitigation potentials within the agenda for sustainable development. *Environ. Res. Lett.* **16**, 024006 (2021).
72. Pörtner, H.-O. et al. Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science* **380**, eabl4881 (2023).
73. Li, W. et al. Mapping the yields of lignocellulosic bioenergy crops from observations at the global scale. *Earth Syst. Sci. Data* **12**, 789–804 (2020).
74. Egerer, S. et al. How to measure the efficiency of bioenergy crops compared to forestation. *Biogeosciences* **21**, 5005–5025 (2024).
75. Smith, P. et al. Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Change* **6**, 42–50 (2016).

76. Butnar, I., Broad, O., Solano Rodriguez, B. & Dodds, P. E. The role of bioenergy for global deep decarbonization: CO2 removal or low-carbon energy? *GCB Bioenergy* **12**, 198–212 (2020).
77. Strefler, J. et al. Between Scylla and Charybdis: delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett.* **13**, 044015 (2018).
78. Grant, N., Hawkes, A., Mittal, S. & Gambhir, A. The policy implications of an uncertain carbon dioxide removal potential. *Joule* **5**, 2593–2605 (2021).
79. Soergel, B. et al. A sustainable development pathway for climate action within the UN 2030 Agenda. *Nat. Clim. Change* **11**, 656–664 (2021).
80. Humpenöder, F. et al. Food matters: dietary shifts increase the feasibility of 1.5 °C pathways in line with the Paris Agreement. *Sci. Adv.* **10**, eadj3832 (2024).
81. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).
82. Lund, J. F., Markusson, N., Carton, W. & Buck, H. J. Net zero and the unexplored politics of residual emissions. *Energy Res. Soc. Sci.* **98**, 103035 (2023).
83. Buck, H. J., Carton, W., Lund, J. F. & Markusson, N. Why residual emissions matter right now. *Nat. Clim. Change* **13**, 351–358 (2023).
84. Edelenbosch, O. Y. et al. Reducing sectoral hard-to-abate emissions to limit reliance on carbon dioxide removal. *Nat. Clim. Change* **14**, 715–722 (2024).
85. Strefler, J. et al. Carbon dioxide removal technologies are not born equal. *Environ. Res. Lett.* **16**, 074021 (2021).
86. Fuhrman, J. et al. Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nat. Clim. Change* **13**, 341–350 (2023).
87. Rueda, O., Mogollón, J. M., Tukker, A. & Scherer, L. Negative-emissions technology portfolios to meet the 1.5 °C target. *Glob. Environ. Change* **67**, 102238 (2021).
88. Gough, C. et al. Challenges to the use of BECCS as a keystone technology in pursuit of 1.5 °C. *Glob. Sustain.* **1**, e5 (2018).
89. Sandström, V. et al. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. *Nat. Food* **3**, 729–740 (2022).
90. Liu, W. et al. Global estimation of the climate change impact of logging residue utilization for biofuels. *For. Ecol. Manag.* **462**, 118000 (2020).
91. Pour, N., Webley, P. A. & Cook, P. J. Potential for using municipal solid waste as a resource for bioenergy with carbon capture and storage (BECCS). *Int. J. Greenh. Gas. Control* **68**, 1–15 (2018).
92. Rosa, L., Sanchez, D. L. & Mazzotti, M. Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. *Energy Environ. Sci.* **14**, 3086–3097 (2021).
93. Peura, M., Burgas, D., Eyvindson, K., Repo, A. & Mönkkönen, M. Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. *Biol. Conserv.* **217**, 104–112 (2018).
94. Rose, S. K. et al. Global biomass supply modeling for long-run management of the climate system. *Clim. Change* **172**, 3 (2022).
95. Bodirsky, B. L. et al. The ongoing nutrition transition thwarts long-term targets for food security, public health and environmental protection. *Sci. Rep.* **10**, 19778 (2020).
96. Willett, W. et al. Food in the Anthropocene: the EAT Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).
97. Hayek, M. N., Harwatt, H., Ripple, W. J. & Mueller, N. D. The carbon opportunity cost of animal-sourced food production on land. *Nat. Sustain.* **4**, 21–24 (2021).
98. Stehfest, E. et al. Climate benefits of changing diet. *Clim. Change* **95**, 83–102 (2009).
99. Sun, Z. et al. Dietary change in high-income nations alone can lead to substantial double climate dividend. *Nat. Food* **3**, 29–37 (2022).
100. Rueda, O., Mogollón, J. M., Stenzel, F., Tukker, A. & Scherer, L. A protein transition can free up land to tap vast energy and negative emission potentials. *One Earth* **7**, 293–310 (2024).
101. Schueler, V., Weddige, U., Beringer, T., Gamba, L. & Lamers, P. Global biomass potentials under sustainability restrictions defined by the European Renewable Energy Directive 2009/28/EC. *GCB Bioenergy* **5**, 652–663 (2013).
102. Wirth, S. B. et al. Biological nitrogen fixation of natural and agricultural vegetation simulated with LPJmL 5.7.9. *Geosci. Model Dev.* **17**, 7889–7914 (2024).
103. Bondeau, A. et al. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Glob. Change Biol.* **13**, 679–706 (2007).
104. Heck, V., Gerten, D., Lucht, W. & Boysen, L. R. Is extensive terrestrial carbon dioxide removal a 'green' form of geoengineering? A global modelling study. *Glob. Planet. Change* **137**, 123–130 (2016).
105. Werner, C., Lucht, W., Kammann, C. & Braun, J. Land-neutral negative emissions through biochar-based fertilization—assessing global potentials under varied management and pyrolysis conditions. *Mitig. Adapt. Strateg. Glob. Change* **29**, 34 (2024).
106. Schaphoff, S. et al. LPJmL4 – a dynamic global vegetation model with managed land—Part 2: model evaluation. *Geosci. Model Dev.* **11**, 1377–1403 (2018).
107. Jägermeyr, J. et al. Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrol. Earth Syst. Sci.* **19**, 3073–3091 (2015).
108. Ostberg, S., Müller, C., Heinke, J. & Schaphoff, S. LandInG 1.0: A toolbox to derive input datasets for terrestrial ecosystem modelling at variable resolutions from heterogeneous sources. *Geosci. Model Dev. Discuss* **2023**, 1–46 (2023).
109. Yukimoto, S. et al. The Meteorological Research Institute Earth System Model Version 2.0, MRI-ESM2.0: description and basic evaluation of the physical component. *J. Meteorol. Soc. Jpn. Ser. II* **97**, 931–965 (2019).
110. Lange, S. ISIMIP3BASD. *Zenodo*. https://doi.org/10.5281/zenodo.4686991 (2021).
111. Lange, S. et al. *WFDE5 over land merged with ERA5 over the ocean (W5E5 v2.0)*. *ISIMIP Repository* https://doi.org/10.48364/ISIMIP.342217 (2021).
112. Lange, S. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). *Geosci. Model Dev.* **12**, 3055–3070 (2019).
113. Cucchi, M. et al. WFDE5: bias-adjusted ERA5 reanalysis data for impact studies. *Earth Syst. Sci. Data* **12**, 2097–2120 (2020).
114. Breier, J. et al. *lpjmlkit: Toolkit Basic LPJmL Handl. v. 1. 6. 0* https://doi.org/10.5281/zenodo.7773134 (2024).
115. Breier, J. et al. lpjmlkit: A toolkit for operating LPJmL and model-specific data processing. *J. Open Source Softw.* https://doi.org/10.21105/joss.05447 (2024).
116. Hurtt, G. C. et al. Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6. *Geosci. Model Dev.* **13**, 5425–5464 (2020).
117. IUCN&UNEP-WCMC. *The World Database on Protected Areas (WDPA)*, http://www.protectedplanet.net/ (2015).
118. Lehner, B. & Döll, P. Development and validation of a global database of lakes, reservoirs and wetlands. *J. Hydrol.* **296**, 1–22 (2004).
119. Hastings, A. et al. Future energy potential of Miscanthus in Europe. *GCB Bioenergy* **1**, 180–196 (2009).
120. Konis, K. & Schwendinger, F. R Interface to 'lp_solve' v.5.5.2.0.17.7. (2020).
121. Chang, J. et al. Reconciling regional nitrogen boundaries with global food security. *Nat. Food* **2**, 700–711 (2021).

122. de Vries, W., Schulte-Uebbing, L., Kros, H., Voogd, J. C. & Louwagie, G. Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. *Sci. Total Environ.* **786**, 147283 (2021).
123. Schulte-Uebbing, L. F., Beusen, A. H. W., Bouwman, A. F. & de Vries, W. From planetary to regional boundaries for agricultural nitrogen pollution. *Nature* **610**, 507–512 (2022).
124. de Vries, W., Kros, J., Kroeze, C. & Seitzinger, S. P. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Curr. Opin. Environ. Sustain.* **5**, 392–402 (2013).
125. Camargo, J. A. & Alonso, Á. Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. *Environ. Int.* **32**, 831–849 (2006).
126. Poikane, S. et al. Nutrient criteria for surface waters under the European Water Framework Directive: current state-of-the-art, challenges and future outlook. *Sci. Total Environ.* **695**, 133888 (2019).
127. UNEP. *World Atlas of Desertification*. (Arnold, 1997).
128. Skujiņš, J. Nitrogen cycling in arid ecosystems. *Ecol. Bull.* **33**, 477–491 (1981).
129. Gleeson, T. et al. The water planetary boundary: interrogation and revision. *One Earth* **2**, 223–234 (2020).
130. Virkki, V. et al. Globally widespread and increasing violations of environmental flow envelopes. *Hydrol. Earth Syst. Sci.* **26**, 3315–3336 (2022).
131. Pastor, A. V., Ludwig, F., Biemans, H., Hoff, H. & Kabat, P. Accounting for environmental flow requirements in global water assessments. *Hydrol. Earth Syst. Sci.* **18**, 5041–5059 (2014).
132. Stenzel, F., Breier, J. & Braun, J. *Biosphere Integrity Metrics for LPJmL* v. 1.0.2. https://doi.org/10.5281/zenodo.10699198 (2024).
133. Braun, J. et al. Code and data for "Multiple planetary boundaries preclude BECCS outside of agricultural areas". *Zenodo* https://doi.org/10.5281/zenodo.14514051 (2024).

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 869192 (J.B. and C.W.). J.B. is part of the Planetary Boundaries Science Lab's research effort at PIK, which is funded by The Grantham Foundation for the Protection of the Environment. F.S. acknowledges funding by the Global Challenges Foundation through the Future Earth project fund "New Governance Architecture for Addressing Global Systemic Risks". The project has also received support from the German Federal Ministry for Research and Education (BMBF) through the research project STEPSEC (grant number 01LS2102D). We thank Solene Chiquier for providing BECCS carbon removal efficiencies based on the MONET framework.

Author contributions

J.B., C.W., D.G., and W.L conceived the study. J.B. performed and analyzed the simulations, created the figures with support from C.W. and led the discussion and interpretation of results. C.W., F.S., and Si.S. contributed to model development and C.W., D.G. and W.L. contributed to discussions and interpretations of the results. J.B. wrote the paper with input from all authors.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-025-02033-6.

Correspondence and requests for materials should be addressed to Johanna Braun.

Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Fiona Tang and Martina Grecequet. A peer review file is available.

Reprints and permissions information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2025