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Climate and ecological constraints of cultivating bioenergy crops for climate mitigation in tropical regions

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Abstract

Negative-emission approaches, such as bioenergy with carbon capture and storage (BECCS), are expected to play a crucial role in mitigating climate change. However, the capacity for biological carbon sequestration under changing climatic conditions remains highly uncertain, particularly in historically warm regions. Although bioenergy can be derived from various biological materials, nearly all operational BECCS facilities capture CO₂ from bioethanol fermentation. We therefore assess the share of bioenergy crop cultivation that will be exposed to future climate conditions beyond their historically safe climate space (SCS), focusing on tropical regions. We find that 30.5 to 40.3%, 10.4 to 13.0%, and 7.4 to 10.2% of existing oil palm, sugarcane, and soybean production will occur in locations surpassing the SCS of these crops by 2060 under lower warming scenarios. If farmers are unable to adapt effectively to emerging climatic conditions, the carbon sequestration capacity of bioenergy crops in tropical regions could substantially decline under the 2 °C warming target, with reductions of up to 67% for oil palm. However, if farmers instead overcome climatic constraints and expand cultivation in the tropics, conversion of land with an average aboveground carbon storage of around 0.45 Tg C per 100 km² and roughly 600 individual species per 100 km² would result in substantial reductions in ecosystem carbon and biodiversity losses that could outweigh the climate benefits of biofuel-based mitigation.

Significance statement

This research highlights the challenges of expanding bioenergy crop cultivation in the tropics, a potentially crucial strategy for offsetting human-driven carbon emissions and mitigating climate change. Our analysis shows that substantial portions of the tropics will become unfavorable for bioenergy crop cultivation due to climate change, precisely when climate models show that increased negative emissions are most needed. If, instead, projected climatic changes are overcome, expanding bioenergy crop cultivation in tropical regions could severely impact natural carbon storage and biodiversity. These findings underscore the need to critically evaluate the ecological costs and long-term viability of bioenergy strategies in tropical regions, while recognizing the complex trade-offs between climate goals and conservation.

Introduction

Limiting climate warming to ~2 °C will likely require negative emissions from biotic and abiotic sources (1–6). While abiotic approaches such as direct air capture show promise, they remain prohibitively costly and are not yet scalable to levels sufficient enough to meaningfully offset anthropogenic CO₂ emissions. In contrast, biological negative-emission approaches, such as bioenergy with carbon capture and storage (BECCS), are more technologically mature, but first-generation biofuel feedstocks

require substantial land area (1, 4, 7–9), raising concerns about potential land-use conflicts among negative-emission deployment, ecosystem conservation, and food production (10–13). Climate change further exacerbates these challenges by constraining where feedstocks can be viably cultivated (14–16). Biofuels can be derived from various sources, each of which presents unique environmental, economic, and technological challenges. First-generation biofuels are generally derived directly from food crops and require less processing, but they also put additional pressure on the global agricultural system and can

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lead to further land clearing and loss of intact ecosystems. In contrast, second- and third-generation biofuels are made from agricultural residues and high-oil-content biomass, such as algae, but require more complex and costly production methods (17–20).

Despite ongoing constraints, continued investments in carbon-intensive technologies suggest that future emission reductions alone may not be sufficient to stabilize temperatures 2 °C. As a result, integrated assessment models often rely on BECCS to account for a substantial portion of negative-emission capacity in lower climate change scenarios (13, 21). However, rapidly scaling first-generation biofuel production could accelerate rates of land-use conversion, which is particularly concerning in regions already experiencing rapid transformation (1, 22–24). Land clearing is pronounced in the tropics, where high demand for agriculture has driven persistently high deforestation rates over the past several decades (25–29). Although rates of agricultural expansion have slowed globally, tropical regions continue to experience substantial land conversion driven by increased agricultural demand, a trend that is expected to persist in the coming decades (25, 30, 31).

While there is a growing body of evidence on the land-use ramifications of biotic negative-emission technologies (5, 13, 32–34), much of this research has focused on land-use conversion, carbon sequestration rates, and potential conflicts with agricultural systems at the global scale (1–4, 35, 36). Yet limited attention has been given to how climate change may modify the climatic conditions experienced by first-generation biofuel feedstock crops in tropical regions. Studies based on large, coordinated modeling efforts, including the Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Global Gridded Crop Model Intercomparison (GGCMI), have used process-based crop models driven to assess future yield responses across major crops and regions (37–40). These studies generally project that climate change will result in yield declines for major crops in the tropics under ~2 °C of warming but demonstrate substantial spatial heterogeneity in yield responses across tropical regions and crop types. Similarly, the ecological trade-offs associated with expanding bioenergy crop cultivation into tropical ecosystems remain under-evaluated despite the competing demands for land in the region. To address this gap, we assess the climatic and ecological constraints of cultivating first-generation bioenergy crops in the tropics under a 2 °C climate pathway, and also evaluate whether this mitigation strategy remains feasible if global warming exceeds internationally agreed upon targets and instead reach 2.5 °C of warming (i.e. ssp126 and ssp245). We focus on first-generation biofuels due to their feedstock availability, scalability, and ease of integration into the existing energy system, as well as their primary role in current BECCS operations worldwide (17, 41–44). Moreover, first-generation biofuel crops offer an immediately scalable route for rapid BECCS deployment, as existing facilities depend almost entirely on capturing CO₂ from bioethanol fermentation (42–46). However, it should be noted that our study does not evaluate the adaptive capacity of farmers or future crop cultivars nor does it consider the effects of CO₂ fertilization on crop cultivation, which might alter the results presented here. Instead, we estimate the share of current bioenergy crop cultivation that occurs in regions where the climate is expected to shift outside historical growing conditions under both the 2 and 2.5 °C scenarios.

Results

In lower warming scenarios, global mean temperature is largely stabilized through a combination of steep anthropogenic emission reductions and a substantial increase in bioenergy production (Fig. 1). Under the 2 °C scenario, annual anthropogenic CO₂ emissions peak at ~40 Gt CO₂ per year before reaching net zero between 2060 and 2080 (Fig. 1a). Similarly, median atmospheric CO₂ concentrations plateau in the late 2050s and 2060s in the 2 °C scenario, with average scenario bioenergy production increasing to ~8 (2.5 to 14) Gt of dry biomass per year in 2100 (Fig. 1c). In contrast, in the 2.5 °C scenario, median atmospheric CO₂ concentrations reach their maximum around the end of the century, and bioenergy production rises to nearly 5 (1 to 16) Gt of dry biomass per year in 2100 (Fig. 1d). Many mitigation pathways that successfully avoid more extreme climate warming assume large-scale deployment of negative-emission technologies, particularly BECCS. However, the median life-cycle cost of BECCS is ~\$200 per ton of CO₂, which is higher than most nature-based options but lower than the median estimate for direct air capture and storage (Fig. S1 and Table S2). In some cases, BECCS costs exceed \$400 per ton of CO₂ removed, surpassing the costs of other carbon-removal approaches, including carbon capture and storage, enhanced weathering, and soil carbon sequestration, by \$50 to \$300 per ton of CO₂ removed.

Despite climate models projecting an increase in global bioenergy production by midcentury, our analysis reveals that a substantial share of current crop production occurs in regions that will be exposed to conditions outside their historical safe climate space (SCS), limiting the availability of feedstocks for biofuel production. Notably, a large share of existing rainfed crop production occurring in the tropics resides in locations that will experience agriculturally unfavorable climates by 2060 under 2 and 2.5 °C of warming. This specifically includes 30.5 to 40.3%, 14.4 to 19.0%, 10.4 to 13.0%, and 7.4 to 10.2% of oil palm, rice, sugarcane, and soybean existing production in the tropics (Fig. 2a). However, there is substantial heterogeneity across tropical regions, as larger shares of oil palm, sorghum, and soybean production in Asia, Africa, and South America, respectively, would be exposed to unfavorable conditions by midcentury. As climate change progresses, there is a nearly consistent increase in the fraction of production exposed to climatic conditions exceeding their SCS through the century (Fig. 2b–i). Notably, at its peak in 2070, over 30% of oil palm cultivation takes place outside its optimal climate range, whereas ~11% of sugarcane production is expected to face unfavorable climatic conditions in the same timeframe.

Historically, crop production has been highest in locations outside tropical moist forests, in regions where the average annual vegetation carbon density is <0.5 Tg C per 100 km² (Fig. 3). Still, the increased demand for biofuels could incentivize farmers to expand crop cultivation into previously undisturbed areas, posing a direct trade-off with the carbon-sequestration capacity of neighboring ecosystems. Cassava, rice, sorghum, and soybean are the predominant crops that have displaced moist tropical forests and are cultivated in regions where 7.5 to 13% of these forests have been converted to croplands (Fig. 3b, e–g). In dry tropical forests and shrublands, soybeans, sorghum, rice, and maize have been cultivated in areas where, over the past two decades, cropland expansion has displaced 8–10% of these

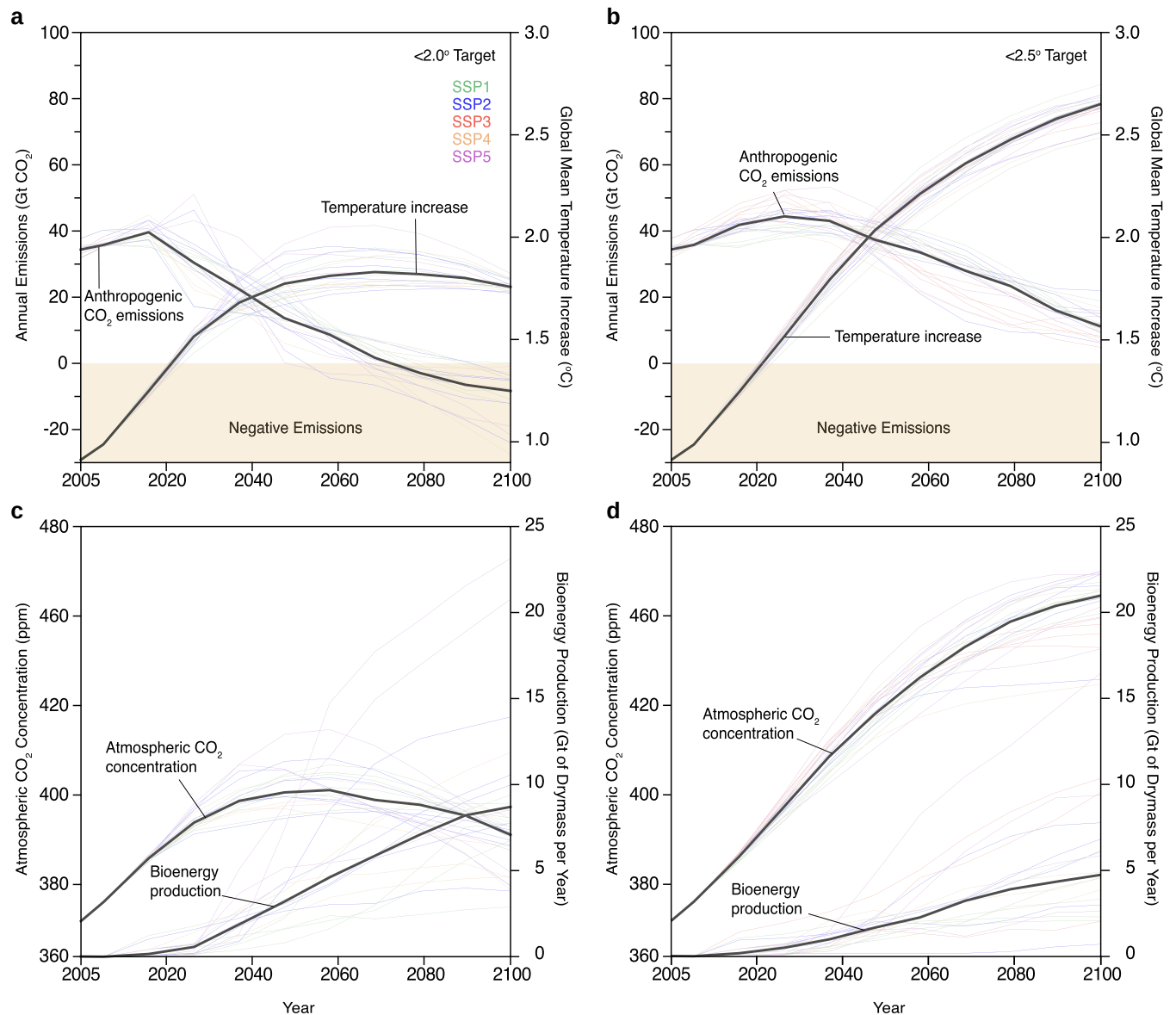


Figure 1 Future temperature, bioenergy production, anthropogenic CO₂ emissions, and atmospheric CO₂ concentration projections. a and b display future temperature projections based on SSP data hosted by the IIASA alongside anthropogenic emissions. In contrast, c and d focus on atmospheric CO₂ concentrations and compare them with bioenergy cultivation. In all cases, the colored lines represent individual SSP ensemble projections, while the black line depicts median projections. a and c represent pathways with a <2 °C increase, while b and d illustrate scenarios to stabilize future climate at <2.5 °C.

ecosystems. Unsurprisingly, carbon sequestration rates in natural environments generally far exceed those observed in croplands across tropical regions, often by orders of magnitude (Fig. S2). Net primary production rates are highest along the western Amazonian Basin, southeastern Brazil, the Congo Basin, and northern Laos and Myanmar, where annual carbon uptake reaches ~ 0.15 Tg C per 100 km² (Fig. S3). Similar levels of carbon uptake are observed in only a few agricultural regions, notably sugarcane and soybean fields in southern Brazil and oil palm plantations on the Malaysian Peninsula and the islands of Borneo and Sumatra (Fig. S3k, t, and w). The highest carbon uptake potential for biofuel is produced from oil palm, soybean, and maize (Fig. 4a). However, the ability of these crops to continue sequestering carbon is largely diminished in future climate warming scenarios (Fig. 4b).

Large trade-offs exist between biofuel crop production, existing carbon sequestration by tropical ecosystems, and biodiversity conservation in tropical regions, particularly if crop management efforts successfully mitigate anticipated climate damages (Fig. 5). On average, tropical regions store ~ 0.45 Tg C and host ~ 600 individual vertebrate species per 100 km², whereas intact tropical forests contain ~ 1.47 Tg C per 100 km². Our analysis also compares the species richness and average annual live biomass carbon storage across tropical ecosystems, revealing that expanding crop cultivation for biofuel production could have adverse effects on biodiversity and natural carbon storage across the tropics. We find more favorable conditions for biofuel crop cultivation in Central America, southern Mexico, Indonesia, Brunei, Malaysia, and the Philippines. However, expanding crop production in these areas would directly conflict with locations

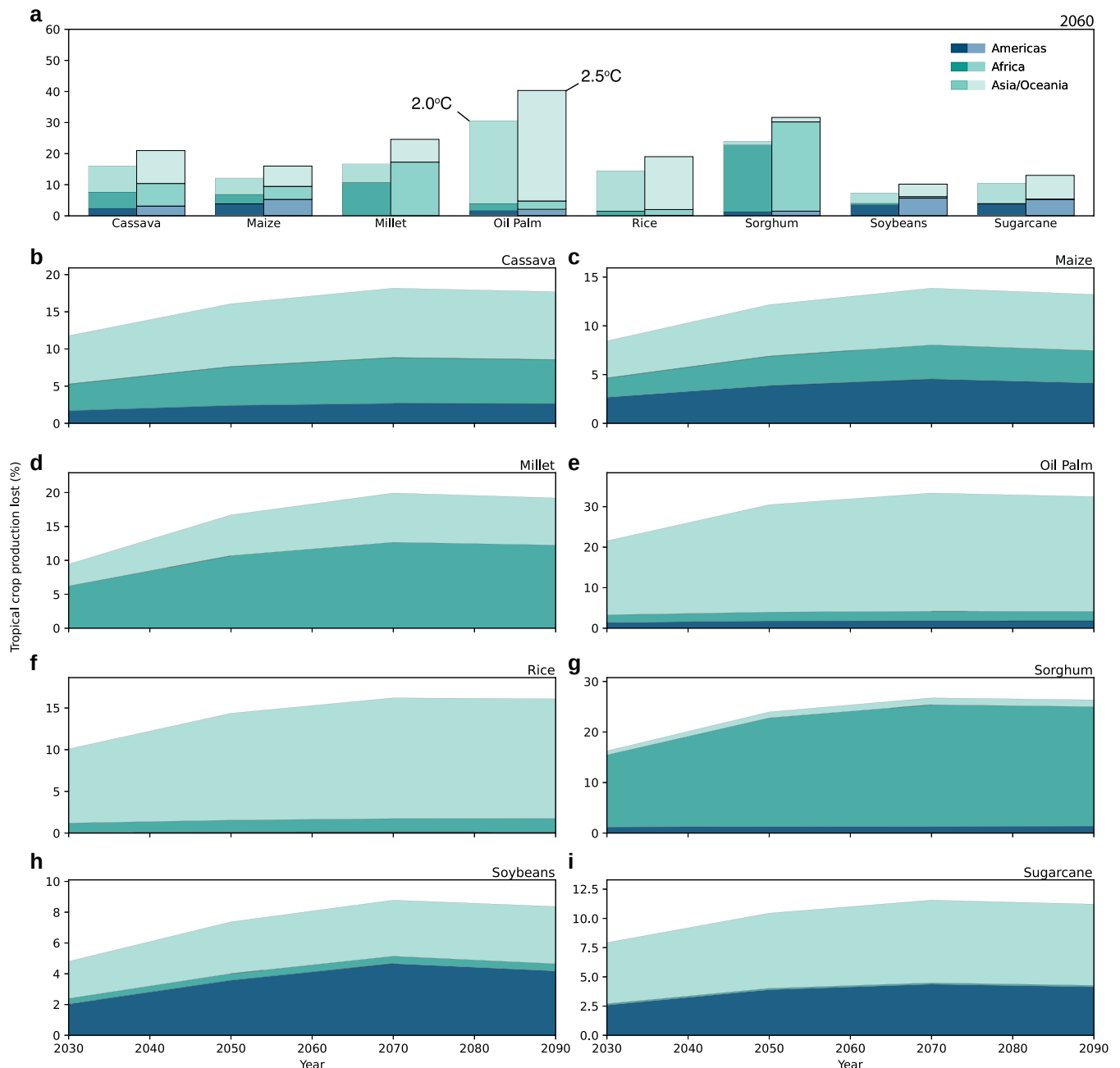


Figure 2 Share of crop production occurring in tropical areas exceeding their SCS under future climate scenarios. a) The proportion of total crop production occurring beyond its historical SCS in 2060 under 2 and 2.5 °C warming, illustrated by region (colors). b–i show how tropical crop production shifts outside its SCS over time under 2 °C of warming.

of high biodiversity and carbon storage, as these regions are among the most biodiverse on the planet, with an average of 800 to 1,200 individual species per 100 km². Therefore, expanding crop cultivation within the Amazonian basin, northern Myanmar, Laos, Thailand, Malaysia, Bhutan, the Republic of Congo, Cameroon, Gabon, and Equatorial Guinea could lead to substantial declines in natural carbon storage and biodiversity (Fig. 5a). Conversely, southern Brazil, Malawi, Tanzania, and Zambia show high species richness (e.g. 649 to 829 individual species per 100 km²) but low levels of aboveground biomass (AGB; ~0.12 to 0.27 Tg per 100 km²). Much of Papua, the Philippines, eastern Madagascar, parts of eastern India, and

the Mexican highlands exhibit relatively lower species richness (~264 to 554 individual species per 100 km²) with moderate AGB (~0.30 to 0.97 Tg C per 100 km²). In addition to carbon stocks and species richness, we also examined the spatial relationship between croplands and remaining intact tropical forests. Many crop areas are directly adjacent to intact forested regions (Figs. 5 and S6), particularly in the Amazon and Congo Basins and across the island of Borneo. These regions contain some of the last extensive, intact tropical forests, and have some of the highest concentrations of species (1127, 583, and 716 individual species per 100 km² area, respectively) and aboveground carbon stocks (0.96, 0.66, and 0.92 Tg C per 100 km²,

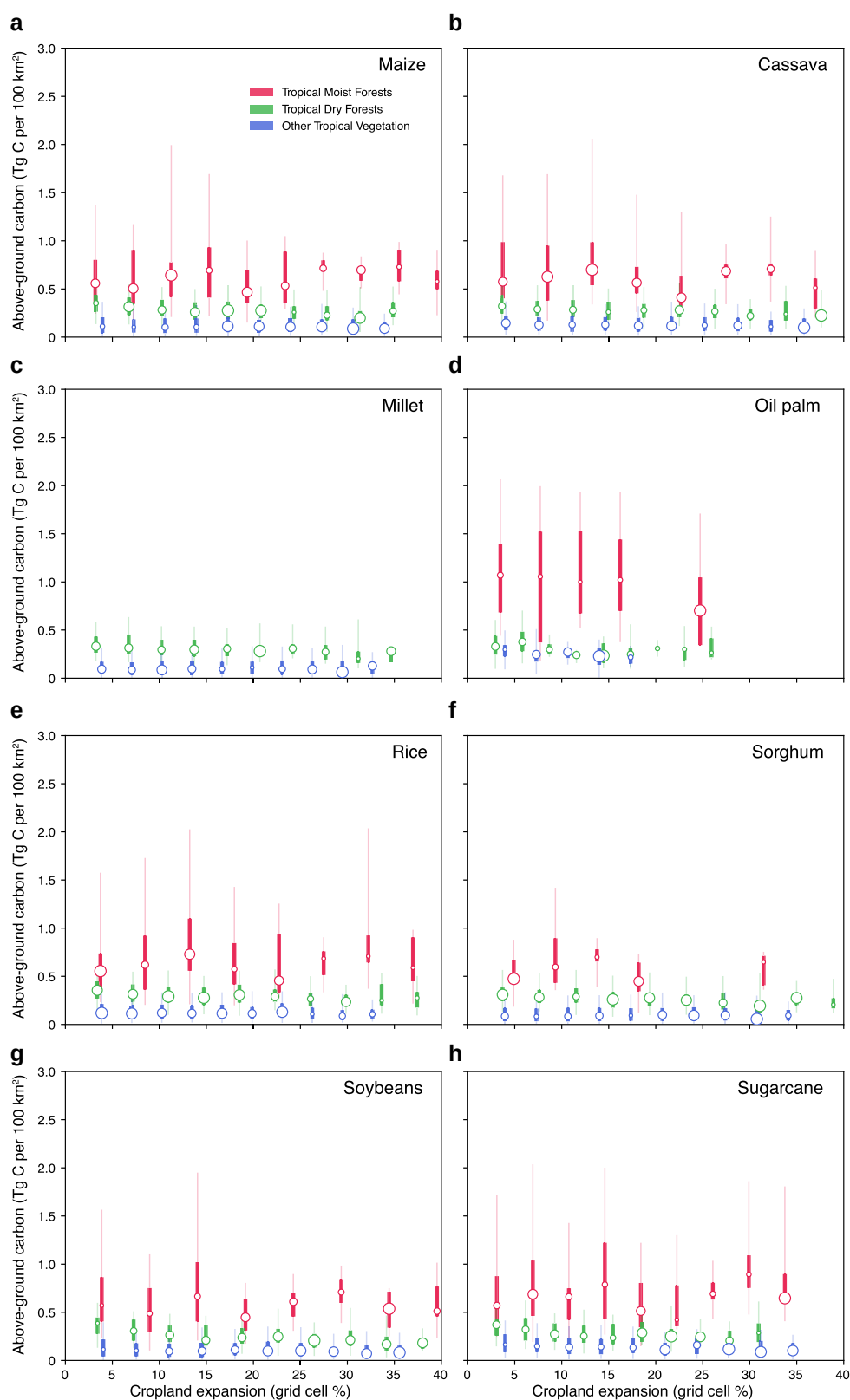


Figure 3 Cropland dynamics in tropical regions. Panels a–h show the relationship between cropland expansion (x-axis, % of grid cell) and aboveground carbon storage (y-axis, Tg C 100 km²) for a given rainfed crop used for bioenergy production. Vertical whiskers indicate the 5th–95th percentile (thin line) and 25th–75th percentile (thick line) of carbon storage in binned cropland expansion intervals, weighted by cropland area within each ecoregion. Colors show tropical moist forests (red), tropical dry forests (green), and other tropical vegetation (blue). White-filled circles with colored edges indicate the weighted mean carbon storage in each bin, with circle size corresponding to the relative production of each crop. Gold and dark green stars mark the weighted-mode and 90th-percentile intersections between crop production and carbon storage, respectively.

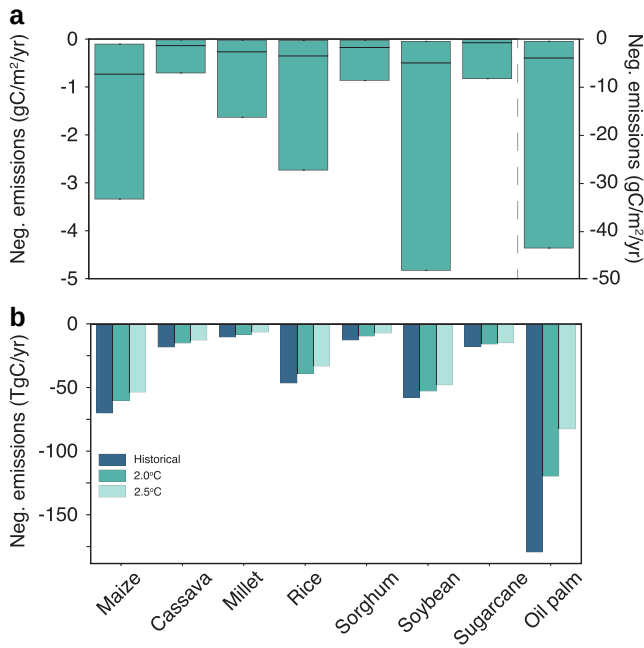


Figure 4 Change in cropland negative-emission potential. a) The grid-cell distribution of negative-emission potential for bioenergy crops (left y-axis) and for oil palm (right y-axis). b) Projected changes in the negative-emission potential of bioenergy crops under historical conditions and future climate scenarios (colors) aggregated across tropical regions.

respectively) on the planet. The Amazon alone contains 570,763 km² of intact forest, accounting for 68.4% of all intact tropical forest area, while the Congo Basin and Borneo hold ~120,896 and 16,560 km², respectively.

Discussion

Stabilizing global temperatures at 2 °C will likely require negative emissions combined with the rapid phaseout of CO₂-emitting technologies (3, 4, 47, 48). Immediate and steep CO₂ emissions reductions may reduce the need for bioenergy, whereas delayed decarbonization would likely increase the need for extensive negative-emission deployments to meet more stringent climate targets (21, 49, 50). First-generation biofuels face substantial challenges in tropical regions, potentially limiting their role in mitigating climate change (18, 19). Even under modest warming scenarios, changing climatic conditions potentially undermine the feasibility of this mitigation pathway if bioenergy deployment is substantially delayed, unless cultivation expands into areas with more favorable conditions to compensate for climate-induced losses (51). Process-based crop model ensembles (e.g. GGCMI and AgMIP) indicate that some major crops may not experience substantial declines in certain regions due to CO₂ fertilization and increased adaptation efforts despite an additional ~2 °C of warming (38, 40). Our results do not

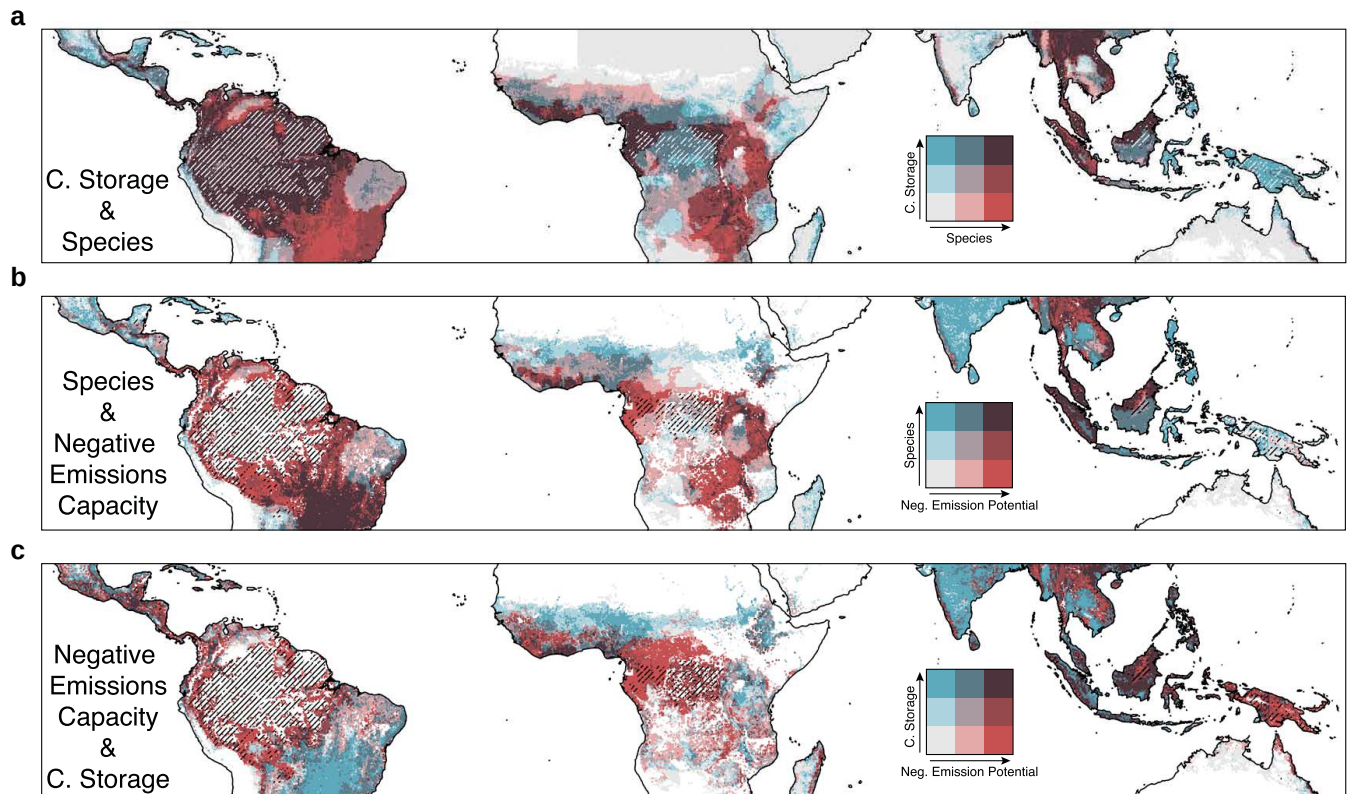


Figure 5 Choropleth bivariate maps of negative-emission potential and ecological trade-offs from expanding biofuel crops in historically cultivated areas. In a, bluer areas indicate a higher concentration of AGB, while red hues suggest greater species richness, and hatches show areas of intact tropical forests. a and c compare species richness and AGB with the average negative-emission potential from crops included in this study. Red hues represent negative-emission potential, while blue colors indicate the trade-offs in these panels. In b and c, white areas indicate regions where none of the crops included in this study have been historically cultivated.

contradict these findings but rather identify where future conditions depart from the climatic envelope under which current crop production has occurred. It should be noted that exceeding this envelope does not imply immediate yield decline but highlights where farmers will have to adapt to new conditions (e.g. by increasing their dependence on untested cultivars, management, and resource inputs). Still, overcoming future climatic barriers to first-generation bioenergy production would provide minimal mitigation of the broader tension between carbon-removal goals relying on land-intensive strategies and biodiversity preservation across the world's most species- and carbon-rich landscapes.

Rising demand for food and energy is expected to intensify pressure on existing agricultural land, potentially leading to further expansion and substantially reducing net carbon storage because these crops retain only a fraction of the carbon and species present in native vegetation. While the infrastructure needed to scale biofuel production in tropical regions remains underdeveloped and lacks the economic framework to support rapid expansion (52, 53), these limitations may be overcome as future demand for bioenergy grows. To deliver lasting climate-mitigation benefits, CO₂ absorbed during cultivation must be captured at combustion and durably sequestered in long-term geologic reservoirs, such as depleted oil and gas reservoirs, deep saline aquifers, or unmineable coal seams (54–56). Thus, without strategic and coordinated land-use planning, the infrastructure required to support BECCS (e.g. large-scale pipeline networks and road development) would further fragment tropical ecosystems (57–62).

It is important to note that our study does not encompass all crops that can be used to produce bioenergy, nor is it focused solely on those with the greatest potential under future climate scenarios. Instead, we evaluate eight crops widely cultivated in tropical regions that have historically been used for first-generation biofuel production (63–65), irrespective of their carbon sequestration capacity or abundance as primary feedstocks. We also do not account for life-cycle emissions or the climate-mitigation benefits of displacing fossil energy sources, which, although critical, are beyond the scope of this analysis. Similarly, we exclude potential CO₂ fertilization benefits given the uncertainty surrounding the yield response from elevated atmospheric CO₂ under ambient conditions in tropical environments (e.g. nutrient limitations and extreme heat exposure), particularly for crops with different photosynthetic pathways (i.e. C₃ vs. C₄) (66–68). Our methodological framework, in contrast, isolates how climate exposure in existing croplands is projected to shift with warming, providing a foundation for evaluating the challenges of cultivating first-generation biofuel feedstocks under future scenarios. In some cases, the negative effects of an unfavorable climate may be partially offset by adopting more resilient crop varieties or expanding irrigation, although the effectiveness of these approaches remains uncertain (69, 70). Alternatively, second-generation biofuel feedstocks, such as *Miscanthus*, Guinea grass, and Napier grass, offer higher carbon sequestration rates and can often be grown on marginal lands, potentially reducing pressure on more productive agricultural areas (34, 71, 72). Yet bioenergy derived from lignocellulosic biomass such as perennial grasses remains economically unviable without the co-production of other high-value products, currently limiting its scalability (72–74).

Ultimately, avoiding the most severe impacts of climate change requires an immediate and sustained shift away from fossil energy sources (21, 47, 75–77), which remain the dominant source of anthropogenic CO₂ emissions (78). Negative-emission technologies such as BECCS can be essential to ease the transition away from CO₂-emitting infrastructure and achieve lower mitigation targets (4, 5, 17, 49). However, agricultural production is also a major source of greenhouse gas emissions and a primary driver of global deforestation and species loss (78–80). Therefore, as climate change mitigation strategies are developed and debated, it is essential to balance these efforts with the protection of ecosystem functions that support biodiversity, carbon storage, and human well-being. Species extinctions are irreversible and can trigger cascading effects across both natural and human systems, underscoring the importance of integrated climate mitigation, energy, agriculture, and conservation policy (81–83). Tropical forests store the highest concentrations of aboveground carbon (59) and biodiversity on Earth and support the livelihoods of over a billion people, making them an essential region for evaluating the environmental trade-offs posed by climate-mitigation strategies that intensify pressures on already vulnerable ecosystems. Ensuring that climate-mitigation efforts do not come at the expense of regional ecosystems is critical for delivering truly sustainable and equitable climate change solutions.

Methods

We evaluated how future climate change could constrain the cultivation of crops historically used for first-generation biofuels in tropical regions. Our analysis focuses on eight rainfed crops that can be used to produce bioenergy (i.e. maize, cassava, oil palm, millet, rice, sorghum, soybeans, and sugarcane). These crops were selected for their established role as bioenergy feedstocks, their prevalence in tropical regions, and the availability of high-resolution data. We adopted the SCS framework to identify the climatic envelope under which current production of these crops occurs and to evaluate where future climate conditions are projected to exceed this historical range in existing croplands within tropical regions.

To define the SCS for each crop, we characterized baseline climate conditions using monthly mean temperature and total precipitation from WorldClim 2 (84), aggregated these values to annual estimates, and mapped each grid point following the Holdridge Life Zone approach (85, 86). Rainfed cropping data were obtained from the Global Agro-Ecological Zones dataset (GAEZ v3.0), produced by the UN Food and Agriculture Organization (FAO) and International Institute for Applied Systems Analysis (IIASA) (87), which provides global crop production at 5-arcminute spatial resolution. For each crop, we extracted the corresponding annual climate values from the historical baseline period, which represents the 30-year climatology averaged from 1970 to 2000. In alignment with past studies, we identified the climatic envelope that encompasses 95% of total global rainfed production (85, 86). The 95th percentile captures the dominant production areas, while the lowest 5% were excluded to remove marginal regions where cultivation occurs under low-yield conditions. Future climate projections were also obtained from the WorldClim 2 database, which provides bias-corrected and downscaled CMIP6 outputs at the same five

arcminute resolution. We used monthly mean projections of maximum temperature, minimum temperature, and precipitation from 14 global climate models under the SSP126 and SSP245 scenarios. Each model output represents the average climate over 20-year periods (2021–2040, 2041–2060, 2061–2080, and 2081–2100). We derived multimodel ensemble averages for each variable and period, which were used to quantify projected changes in climate conditions within tropical cropping areas. A complete list of the global climate models used in this study is available in Table S1.

For each grid cell containing crop production within tropical regions, we computed the annual mean temperature and total precipitation for each future 30-year period and compared these values with the historical SCS envelope. Grid cells where future climate conditions remain within the historical bounds were classified as inside the SCS, while those exceeding either the temperature or precipitation limits were classified as outside the SCS. To quantify potential production losses, we applied the SCS masks to the current distribution of rainfed crop production. For each crop and scenario, we calculated the proportion of the existing tropical cultivation area projected to remain within or move beyond its historical climatic range. This approach provides a consistent and spatially explicit measure of how climate change may alter the geographic extent of suitable growing conditions across major bioenergy crops.

Future projections of CO₂ emissions, atmospheric CO₂ concentration, and bioenergy production were obtained from the IIASA shared socioeconomic database. We included all available models under the 2 and 2.5 °C scenarios, calculated the median projection, and presented the full range of results. To evaluate the ecological implications of potential cropland expansion, we assessed vertebrate species richness and AGB across tropical regions and compared their distributions with the carbon sequestration potential of BECCS. Vertebrate species richness was derived from the IUCN Red List raster (version 2025-2), which reports the number of amphibian, bird, mammal, and reptile species within each 10 × 10 km cell. Annual AGB carbon values were obtained from Xu et al. (88), with AGB values averaged from 2000 to 2020. Bioenergy carbon sequestration potential was calculated following the Xu et al. (51) methodology and averaged across all bioenergy crops. Each data layer was rescaled to express its value as a percentage of its maximum value and classified into three equal-frequency categories: low (<25th percentile), medium (25th–75th percentiles), and high (>75th percentile) to facilitate visual interpretation. We used the Intact Forest Landscape dataset from Potapov et al. (2017) (89) to illustrate areas where bioenergy expansion could potentially degrade intact forests. We then generated bivariate maps to depict spatial overlap among ecological metrics, BECCS potential, and intact forest areas, highlighting regions where cropland expansion would present the greatest ecological risks.

To compare the carbon uptake potential of croplands cultivated for bioenergy with that of tropical ecosystems, we analyzed net primary production (NPP) and net ecosystem production across both uncultivated and cultivated lands. Natural vegetation NPP was obtained from the Moderate Resolution Imaging Spectroradiometer, which provides annual estimates from 2001 to 2020. Cropland NPP was estimated using the method described in Xu et al. (51), where NPP is calculated as the product of total production, the fraction of dry biomass, the

fraction of biomass in shoots, and the fraction of carbon in dry biomass (51). To isolate the contribution of natural vegetation in mixed-use grid cells, we subtracted cropland NPP from the total NPP for each grid point that included one or more of the crops analyzed in this study. Cost ranges for carbon dioxide removal technologies were obtained from the S&P Global 2023 report (90), which aggregated estimates published by the IEA (91) and IPCC AR6 WG III (92). Carbon dioxide removal (CDR) ranges shown in Fig. S1 and Table S2 represent technology-specific life-cycle capital and operating costs expressed in US dollars per ton of CO₂ removed.

Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

Competing Interest

The authors declare no competing interests.

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Author Contributions

Robert Fofrich Navarro (Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review & editing), Alcen Chiu (Data curation, Formal analysis, Writing—review & editing), and Elsa M. Ordway (Conceptualization, Methodology, Project administration, Resources, Supervision, Visualization, Writing—review & editing)

Data Availability

All data used within this study are publicly available. Data processing and analysis were conducted in MATLAB and Python. The underlying code to produce these results is available at <https://github.com/rfofrich/Constraints-of-cultivating-bioenergy-crops-for-climate-mitigation-in-tropical-regions.git>.

References

1. Turner PA, Field CB, Lobell DB, Sanchez DL, Mach KJ. 2018. Unprecedented rates of land-use transformation in modelled climate change mitigation pathways. *Nat Sustain.* 1:240–245.
2. Nolan CJ, Field CB, Mach KJ. 2021. Constraints and enablers for increasing carbon storage in the terrestrial biosphere. *Nat Rev Earth Environ.* 2:436–446.
3. Azar C, Johansson DJA, Mattsson N. 2013. Meeting global temperature targets—the role of bioenergy with carbon capture and storage. *Environ Res Lett.* 8:034004.

4. Muri H. 2018. The role of large-scale BECCS in the pursuit of the 1.5°C target: an Earth system model perspective. *Environ Res Lett.* 13:044010.
5. Minx JC, et al. 2018. Negative emissions—part 1: research landscape and synthesis. *Environ Res Lett.* 13:063001.
6. Peters GP. 2016. The ‘best available science’ to inform 1.5°C policy choices. *Nat Clim Chang.* 6:646–649.
7. Lambin EF, Meyfroidt P. 2011. Global land use change, economic globalization, and the looming land scarcity. *Proc Natl Acad Sci U S A.* 108:3465–3472.
8. Dolan F, et al. 2022. Modeling the economic and environmental impacts of land scarcity under deep uncertainty. *Earth's Future.* 10:e2021EF002466.
9. Harper AB, et al. 2018. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nat Commun.* 9:2938.
10. Sills J, Gómez-González S, Ochoa-Hueso R, Pausas JG. 2020. Afforestation falls short as a biodiversity strategy. *Science.* 368:1439.
11. Bond WJ, Stevens N, Midgley GF, Lehmann CER. 2019. The trouble with trees: afforestation plans for Africa. *Trends Ecol Evol.* 34:963–965.
12. Holl KD, Brancalion PHS. 2020. Tree planting is not a simple solution. *Science.* 368:580–581.
13. Fuss S, et al. 2018. Negative emissions—part 2: costs, potentials and side effects. *Environ Res Lett.* 13:063002.
14. Baldocchi D, Penuelas J. 2019. The physics and ecology of mining carbon dioxide from the atmosphere by ecosystems. *Glob Chang Biol.* 25:1191–1197.
15. Anderson CM, et al. 2019. Natural climate solutions are not enough. *Science.* 363:933–934.
16. Anderegg WRL, et al. 2020. Climate-driven risks to the climate mitigation potential of forests. *Science.* 368:eaaz7005.
17. Moodley P. 1—Sustainable Biofuels: opportunities and challenges. In: Ray RC, editor. *Sustainable biofuels*. Academic Press, 2021. p. 1–20.
18. Cavelius P, et al. 2023. The potential of biofuels from first to fourth generation. *PLoS Biol.* 21:e3002063.
19. Lee RA, Lavoie J-M. 2013. From first- to third-generation biofuels: challenges of producing a commodity from a biomass of increasing complexity. *Anim Front.* 3:6–11.
20. Aro E-M. 2016. From first generation biofuels to advanced solar biofuels. *Ambio.* 45:24–31.
21. Rogelj J, et al. 2018. Scenarios towards limiting global mean temperature increase below 1.5°C. *Nat Clim Chang.* 8:325–332.
22. Ellis EC, Klein Goldewijk K, Siebert S, Lightman D, Ramankutty N. 2010. Anthropogenic transformation of the biomes, 1700 to 2000. *Glob Ecol Biogeogr.* 19:589–606.
23. Beyer RM, Hua F, Martin PA, Manica A, Rademacher T. 2022. Relocating croplands could drastically reduce the environmental impacts of global food production. *Commun Earth Environ.* 3:49.
24. Ramankutty N, Evan AT, Monfreda C, Foley JA. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochem Cycles.* 22:GB1003.
25. Potapov P, et al. 2022. Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat Food.* 3:19–28.
26. Vancutsem C, et al. 2021. Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Sci Adv.* 7:eabe1603.
27. Giller KE, et al. 2021. Small farms and development in sub-Saharan Africa: farming for food, for income or for lack of better options? *Food Secur.* 13:1431–1454.
28. Georgeou N, et al. 2022. Food security and small holder farming in Pacific Island countries and territories: a scoping review. *PLoS Sustain Transform.* 1:e0000009.
29. Leakey RRB. 2020. A re-boot of tropical agriculture benefits food production, rural economies, health, social justice and the environment. *Nat Food.* 1:260–265.
30. Klein Goldewijk K, Beusen A, Doelman J, Stehfest E. 2017. Anthropogenic land use estimates for the Holocene—HYDE 3.2. *Earth Syst Sci Data.* 9:927–953.
31. Williams DR, et al. 2021. Proactive conservation to prevent habitat losses to agricultural expansion. *Nat Sustain.* 4:314–322.
32. Creutzig F. 2016. Economic and ecological views on climate change mitigation with bioenergy and negative emissions. *Glob Change Biol Bioenergy.* 8:4–10.
33. Kraxner F, et al. 2013. Global bioenergy scenarios—future forest development, land-use implications, and trade-offs. *Biomass Bioenergy.* 57:86–96.
34. Popp A, et al. 2011. The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environ Res Lett.* 6:034017.
35. Beringer TIM, Lucht W, Schaphoff S. 2011. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Glob Change Biol Bioenergy.* 3:299–312.
36. Heck V, Gerten D, Lucht W, Popp A. 2018. Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat Clim Chang.* 8:151–155.
37. Müller C, et al. 2017. Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications. *Geosci Model Dev.* 10:1403–1422.
38. Rosenzweig C, et al. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc Natl Acad Sci U S A.* 111:3268–3273.
39. Ruane AC, et al. 2017. An AgMIP framework for improved agricultural representation in integrated assessment models. *Environ Res Lett.* 12:125003.
40. Franke JA, et al. 2020. The GGCM Phase 2 experiment: global gridded crop model simulations under uniform changes in CO₂, temperature, water, and nitrogen levels (protocol version 1.0). *Geosci Model Dev.* 13:2315–2336.
41. Kowalski Z, et al. 2022. Second-generation biofuel production from the organic fraction of municipal solid waste. *Front Energy Res.* 10:919415.
42. Sanchez DL, Johnson N, McCoy ST, Turner PA, Mach KJ. 2018. Near-term deployment of carbon capture and sequestration from biorefineries in the United States. *Proc Natl Acad Sci U S A.* 115:4875–4880.
43. Milão RFD, Carminati HB, Araújo OQF, de Medeiros JL. 2019. Thermodynamic, financial and resource assessments of a large-scale sugarcane-biorefinery: prelude of full bioenergy carbon capture and storage scenario. *Renew Sustain Energy Rev.* 113:109251.

44. Carminati HB, Milão RFD, de Medeiros JL, Araújo OQF. 2019. Bioenergy and full carbon dioxide sinking in sugarcane-biorefinery with post-combustion capture and storage: techno-economic feasibility. *Appl Energy*. 254:113633.
45. Vacharanukrauh T, et al. 2025. A review on comprehensive strategies for decarbonizing bioethanol production process. *Green Energy Resour*. 3:100153. <https://doi.org/10.1016/j.gerr.2025.100153>
46. Tasmin H, et al. *Deployment of BECCUS value chains in the United States*. North Carolina State University; Idaho National Laboratory, IEA Bioenergy–Technology Collaboration Programme, 2023.
47. Fofrich R, et al. 2020. Early retirement of power plants in climate mitigation scenarios. *Environ Res Lett*. 15:094064.
48. Millar RJ, et al. 2017. Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nat Geosci*. 10: 741–747.
49. Gasser T, Guivarch C, Tachiiri K, Jones CD, Ciais P. 2015. Negative emissions physically needed to keep global warming below 2°C. *Nat Commun*. 6:7958.
50. Rogelj J, et al. 2018. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
51. Xu S, et al. 2022. Delayed use of bioenergy crops might threaten climate and food security. *Nature*. 609:299–306.
52. Nemet GF, et al. 2018. Negative emissions—part 3: innovation and upscaling. *Environ Res Lett*. 13:063003.
53. Peters GP, Geden O. 2017. Catalysing a political shift from low to negative carbon. *Nat Clim Chang*. 7:619–621.
54. Bickle MJ. 2009. Geological carbon storage. *Nat Geosci*. 2: 815–818.
55. Zickfeld K, et al. 2023. Net-zero approaches must consider Earth system impacts to achieve climate goals. *Nat Clim Chang*. 13:1298–1305.
56. Ciotoli G, Procesi M, Etiope G, Fracassi U, Ventura G. 2020. Influence of tectonics on global scale distribution of geological methane emissions. *Nat Commun*. 11:2305.
57. Haddad NM, et al. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci Adv*. 1:e1500052.
58. Taubert F, et al. 2018. Global patterns of tropical forest fragmentation. *Nature*. 554:519–522.
59. Mo L, et al. 2023. Integrated global assessment of the natural forest carbon potential. *Nature*. 624:92–101.
60. Fischer R, et al. 2021. Accelerated forest fragmentation leads to critical increase in tropical forest edge area. *Sci Adv*. 7: eabg7012.
61. Smith IA, Hutrya LR, Reinmann AB, Marrs JK, Thompson JR. 2018. Piecing together the fragments: elucidating edge effects on forest carbon dynamics. *Front Ecol Environ*. 16: 213–221.
62. Ordway EM, Asner GP. 2020. Carbon declines along tropical forest edges correspond to heterogeneous effects on canopy structure and function. *Proc Natl Acad Sci U S A*. 117: 7863–7870.
63. Rulli MC, Bellomi D, Cazzoli A, De Carolis G, D'Odorico P. 2016. The water-land-food nexus of first-generation biofuels. *Sci Rep*. 6:22521.
64. Kim S, Dale BE. 2004. Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy*. 26: 361–375.
65. Gurgel AC, et al. 2024. Contribution of double-cropped maize ethanol in Brazil to sustainable development. *Nat Sustain*. 7: 1429–1440.
66. Ainsworth EA, Long SP. 2021. 30 years of free-air carbon dioxide enrichment (FACE): what have we learned about future crop productivity and its potential for adaptation? *Glob Chang Biol*. 27:27–49.
67. Ruiz-Vera UM, et al. 2013. Global warming can negate the expected CO₂ stimulation in photosynthesis and productivity for soybean grown in the midwestern United States. *Plant Physiol*. 162:410–423.
68. Gourdji SM, Sibley AM, Lobell DB. 2013. Global crop exposure to critical high temperatures in the reproductive period: historical trends and future projections. *Environ Res Lett*. 8: 024041.
69. Elliott J, et al. 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proc Natl Acad Sci U S A*. 111:3239–3244.
70. Pugh TAM, et al. 2016. Climate analogues suggest limited potential for intensification of production on current croplands under climate change. *Nat Commun*. 7:12608.
71. McCalmont JP, et al. 2017. Environmental costs and benefits of growing Miscanthus for bioenergy in the UK. *Glob Change Biol Bioenergy*. 9:489–507.
72. Larnaudie V, Ferrari MD, Lareo C. 2022. Switchgrass as an alternative biomass for ethanol production in a biorefinery: perspectives on technology, economics and environmental sustainability. *Renew Sustain Energy Rev*. 158:112115.
73. Sulis DB, et al. 2025. Advances in lignocellulosic feedstocks for bioenergy and bioproducts. *Nat Commun*. 16:1244.
74. Zheng B, Yu S, Chen Z, Huo Y-X. 2022. A consolidated review of commercial-scale high-value products from lignocellulosic biomass. *Front Microbiol*. 13:933882.
75. Kriegler E, et al. 2018. Pathways limiting warming to 1.5°C: a tale of turning around in no time? *Philos Trans R Soc A Math Phys Eng Sci*. 376:20160457.
76. Rogelj J, et al. 2015. Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nat Clim Chang*. 5:519–527.
77. Tong D, et al. 2019. Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target. *Nature*. 572:373–377.
78. Friedlingstein P, et al. 2023. Global carbon budget 2023. *Earth Syst Sci Data*. 15:5301–5369.
79. Foley JA, et al. 2005. Global consequences of land use. *Science*. 309:570–574.
80. Harfoot MJB, et al. 2021. Using the IUCN Red List to map threats to terrestrial vertebrates at global scale. *Nat Ecol Evol*. 5:1510–1519.
81. Bergman J, et al. 2023. Worldwide Late Pleistocene and Early Holocene population declines in extant megafauna are associated with *Homo sapiens* expansion rather than climate change. *Nat Commun*. 14:7679.

82. Ceballos G, *et al.* 2015. Accelerated modern human-induced species losses: entering the sixth mass extinction. *Sci Adv.* 1: e1400253.
83. Dirzo R, *et al.* 2014. Defaunation in the Anthropocene. *Science.* 345:401–406.
84. Fick SE, Hijmans RJ. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int J Climatol.* 37:4302–4315.
85. Heikonen S, *et al.* 2025. Climate change threatens crop diversity at low latitudes. *Nat Food.* 6:331–342.
86. Kummu M, Heino M, Taka M, Varis O, Viviroli D. 2021. Climate change risks pushing one-third of global food production outside the safe climatic space. *One Earth.* 4: 720–729.
87. Fischer GN, *et al.* *Global agro-ecological zones assessment for agriculture (GAEZ 2008)*. IIASA and FAO, 2008.
88. Xu L, *et al.* 2021. Changes in global terrestrial live biomass over the 21st century. *Sci Adv.* 7:eabe9829.
89. Potapov P, *et al.* 2017. The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Sci Adv.* 3(1):e1600821.
90. Ellis T, *et al.* Carbon capture, removal, and credits pose challenges for companies. In: Dillon J, Burke RM, Stroeder B, editors. *Sustainability insights | research*. S&P Global, 2023. p. 8–10.
91. IEA. *Projected costs of generating electricity 2020*. International Energy Agency, 2020.
92. Byers E, *et al.* AR6 Scenario Explorer and Database. [accessed 2025 Nov]. data.ece.iiasa.ac.at/ar6/