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RESEARCH ARTICLE

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Assessing the impact of strictly protecting 30%–50% of global land on carbon dynamics in natural and agricultural ecosystems

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Societal Impact Statement

Strictly protected areas for nature conservation are a key policy to benefit biodiversity and climate change mitigation since reduced deforestation and ecosystem restoration enhance carbon stocks. However, there is controversy regarding their potential societal impacts, such as competition for land and food security. Here, we investigate the implications of protecting 30% and 50% of the global ice-free land surface on the spatiotemporal dynamics of ecosystem carbon uptake and losses, agricultural land use and synergies with food production. The study provides insights into the role of protected areas on the global terrestrial carbon store, contributing to climate change mitigation and biodiversity conservation efforts.

Summary

- Agriculture and forestry use around half of the global ice-free land and are major drivers of biodiversity loss. For this reason, the post-2020 Global Biodiversity Framework of the Convention on Biological Diversity (CBD) targets at least 30% of protected global land by 2030.
- This study evaluates the impacts of different land-use change scenarios on the storage of carbon in terrestrial ecosystems and trade-offs and synergies in the global food production system by comparing a reference scenario with no additional protected area expansion targets and two scenarios with strict area-based protection targets of 30% and 50% of the ice-free land surface.
- A net global gain in carbon storage up to 110 PgC was projected for 2056–2060 in the protection scenarios compared to the reference scenario (equivalent to around 10 years of current global anthropogenic C emissions). However, regional disparities in carbon storage are large and include carbon losses in areas identified as having—at least on a decadal perspective—'irrecoverable' carbon.
- In the protection scenarios, cropland expansion in some regions is accompanied by intensification of production with an increase of up to 8% in the use of N fertiliser, which may lead to pollution and additional greenhouse gas emissions.

KEYWORDS
biodiversity, carbon storage, climate change, ecosystem services, land-use change, LPJ-GUESS, PLUM

1 | INTRODUCTION

More than two thirds of the ice-free land surface has been modified by humans, with around half being used intensively for agriculture and forestry (IPCC, 2019). The widespread influence on ecosystems that humans have had underpins the concept of 'anthropogenic biomes' or anthromes (Ellis et al., 2021). Land-cover and land-use changes are among the most important drivers of global biodiversity loss (IPBES, 2019) and are major sources of greenhouse gas emissions, in the form of CO_2 when transforming natural land into managed systems, as well as CH_4 and N_2O from rice paddies, ruminants and/or fertiliser applications in pastures and croplands (IPCC, 2019). Avoiding further natural land conversion into agriculture and restoring ecosystems has potentially considerable co-benefits for climate change mitigation and adaptation (Arneth et al., 2023; Portner et al., 2023; Shin et al., 2022) but is also considered key for halting and reversing biodiversity loss (Arneth et al., 2023; Portner et al., 2023; Shin et al., 2022). However, continued human population growth, changes in per-capita consumption and rapidly accelerating climate change exert large and increasing pressures on restoration objectives. These pressures accelerate the global expansion and intensification of managed land, contributing to continued biodiversity decline (Arneth et al., 2023; Erb et al., 2016). They also explain why most of the Aichi Biodiversity Targets of the Convention on Biological Diversity (CBD) had not been met despite global and national policies to support biodiversity conservation (Buchanan et al., 2020).

The post-2020 Global Biodiversity Framework of the CBD sets out to remedy the failure of the Aichi Biodiversity Targets, particularly with the '30 × 30' target 3, which aims to protect 30% of global ecosystems by the year 2030, and the closely related targets 1 (Biodiversity-inclusive spatial planning) and 2 (Restoration of at least 20% of degraded ecosystems) (Shin et al., 2022; Voskamp et al., 2023). These targets have received substantial attention and controversy since some researchers argue that larger areas of land and sea should be protected to achieve direct benefits for biodiversity and co-benefits such as enhancing carbon sinks and climate change mitigation, while others assert that any area target will be insufficient unless implemented effectively (Arneth et al., 2023; Shin et al., 2022; Voskamp et al., 2023).

Reaching protected area targets requires the transformation of large areas, increasing the competition for land for other human uses, which could affect broader sustainability goals related to ecosystem service provisioning and food security by reducing agricultural area, food production and access and/or increasing food prices (Arneth et al., 2023; Voskamp et al., 2023). Henry et al. (2022) found that negative impacts on food security in response to strict area protections could result in adverse impacts on human health and mortality, particularly in economically vulnerable regions of the world. While these effects could be mitigated through dietary shifts towards lower animal protein consumption in overconsuming regions of the world and/or through reducing food waste and losses (Arneth et al., 2023; Erb et al., 2016), concerns about implementing protected areas in a socially acceptable way that reduces trade-offs with food production need to be better understood.

In this study, land-use change projections from the Land System Modular Model (LandSyMM) were used to examine the impacts of placing 30% and 50% of global land under strict protection (Henry et al., 2022) on ecosystem carbon cycles, cropland expansion and intensification and food production.

2 | MATERIALS AND METHODS

2.1 | LandSyMM

The Land System Modular Model (www.LandSymm.earth) (Alexander et al., 2018; Rabin et al., 2020) is a regional to global scale modelling framework that couples climate, economic, ecological and biophysical processes of environmental change to simulate land-system dynamics. LPJ-GUESS v4.1, a component module of LandSyMM, is a dynamic global vegetation model that simulates ecosystems through physiological, demographic and disturbance processes for a suite of woody, grassy and crop functional types (Olin et al., 2015; Smith et al., 2014). Modelled physiological and hydrological processes in vegetation and soils mostly have daily time steps, whereas vegetation growth, establishment, disturbance and mortality are represented annually. Processes in LPJ-GUESS are driven mainly by climate input, atmospheric carbon dioxide levels and nitrogen deposition.

PLUM v2, another component module of LandSyMM, is a land and food system model that simulates grid cell-level land use and management, demand, prices and international trade for food commodities. The model uses gridded LPJ-GUESS yield potentials under different climate and socioeconomic scenarios (Alexander et al., 2018). PLUM uses least cost optimisation to solve for land-use areas and inputs that satisfy demand, allowing short-term resource surpluses and deficits. In the LandSyMM modelling framework, PLUM integrates 5-year averages of future potential yields from LPJ-GUESS with its future commodity demand to project land-use change and management intensity. The simulated gridded data of land-cover changes, the amount of water irrigated and nitrogen fertiliser in cropland are then used to model changes in ecosystem states and fluxes in LPJ-GUESS (Alexander et al., 2018; Rabin et al., 2020). Figure S1 provides an overview of the LPJ-GUESS and PLUM coupling. Food demand and agricultural land requirements are influenced by the endogenously calculated GDP and food prices; for instance, as GDP rises, diets shift toward increased consumption of meat, dairy, fruits and vegetables, instead of staple crops.

2.2 | Model setup

LPJ-GUESS simulations were performed at a spatial resolution of 0.5 × 0.5° using the climate and CO_2 forcing scenario representative concentration pathway (RCP) 4.5. Forcings were taken from IPSL-CM6B-LR outputs (Tebaldi et al., 2021). PLUM provided the amount of N fertiliser applied to cropland, water used for irrigation and land-use transitions to LPJ-GUESS. The spin-up in LPJ-GUESS follows Rabin et al. (2020), recycling detrended historical climate forcing inputs at a constant CO_2 level to generate an equilibrium ecosystem state. The Land-Use Harmonisation version 2 (LUH2; Hurtt et al., 2020) provided annual net land-use changes for simulations of the historical period, which were spatially harmonised for a smooth transition to PLUM future scenarios (Alexander et al., 2018).

Socioeconomic parameters, population and gross domestic product (GDP) trajectories followed the socioeconomic SSP2 scenario (O'Neill et al., 2016). This scenario assumes moderate annual yield growth of 0.2% due to technological advancements and improved management practices such as fertilisation and irrigation. It also assumes that GDP continues to increase, causing a gradual dietary transition to greater meat, milk, fruits and vegetables consumption and lower staple crop consumption since food demand and agricultural land requirements are affected by the endogenously calculated GDP and food prices (Alexander et al., 2018).

2.3 | Protection scenarios

The land-use scenario projections were generated following the approach in Henry et al. (2022), including a reference scenario with no additional future area-protection target above the present-day and two area-based strict protection scenarios with targets of 30% and 50% of the global ice-free land surface. The conservation prioritisation scheme determined protected area grid cell fractions based on vertebrate distribution data. It incorporated intraspecific variation and genetic diversity by dividing species ranges across terrestrial biomes, emphasising locally important subpopulations to reduce tropical bias in conservation value (Henry et al., 2022; Jung et al., 2021). In both protection scenarios, natural land was protected starting in 2020 in grid cells with sufficient natural land, while in grid cells with low natural land, managed land was gradually converted to meet the required protected area fraction, assuming that urban and barren land areas are unusable for agriculture and unaffected by protected area targets. This process was implemented yearly until the natural land and strictly protected area fractions were equal by 2040. Simulations continued until 2060, allowing the model mechanisms and dynamics to stabilise. It was assumed that protection was implemented in prioritised regions without considering national or regional institutional restrictions, justice and equity concerns, geopolitical events or potential displacement of people.

2.4 | Data analysis

Land-cover fractions, irrigation water and N fertiliser application from PLUM, and total and vegetation carbon (C) pools, net primary production (NPP) and crop yields from LPJ-GUESS, were averaged over 5-year periods for the present-day (2016–2020) and each scenario projection (2056–2060). Variables were aggregated globally and by three different latitude bands (Northern: 25° N–75° N; Tropical: 25° S–25° N; Southern: 25° S–75° S) weighted by the total area (km^2) per grid cell calculated with the function *area* from the R package *raster* (R Core Team, 2021). The total yield, along with irrigation water and N fertiliser application, was estimated by adding up each of these variables from the nine crop functional types (CFTs) simulated in PLUM: wheat, maize, rice, oil crops, pulses, starchy roots, fruits and vegetables, sugar crops and energy crops. These variables were scaled using the total harvested area by CFT, estimated by multiplying each CFT cover fraction, the overall cropland-cover fraction (both obtained from PLUM) and the total area per grid cell.

2.5 | Irrecoverable carbon

The expansion of protected and agricultural areas was compared to previously reported areas containing substantial quantities of irrecoverable C. Irrecoverable C is defined as the C in 2018 that is vulnerable to being lost in a land-cover conversion event, which may not be recovered within 30 years even if the original land cover is restored (Noon et al., 2022). The dataset of irrecoverable C was rescaled using bilinear interpolation from 300 m resolution to 0.5° to make it comparable to LPJ-GUESS outputs. Spatial correlations by latitude bands and scenario were performed between the total irrecoverable C and the total C difference (30% and 50% protection scenario—Reference averaged for 2056–2060). Finally, the irrecoverable C at risk was estimated as the irrecoverable C amount (kgC m^{-2}) in the increased cropland area between 2015–2020 and 2056–2060 for each area protection scenario projection per grid cell and aggregated by latitude band.

3 | RESULTS

The simulated land cover from PLUM for the reference scenario showed a small decrease in natural vegetation of around 2% (138 million ha) between 2016–2020 and 2056–2060, mainly in the tropics around central Africa, Amazon and Southeast Asia. Small areas of agricultural land abandonment were also simulated; for instance, in the southeast of the United States, India and Europe (Figure S2). Protection of 30% and 50% resulted in much stronger land-use

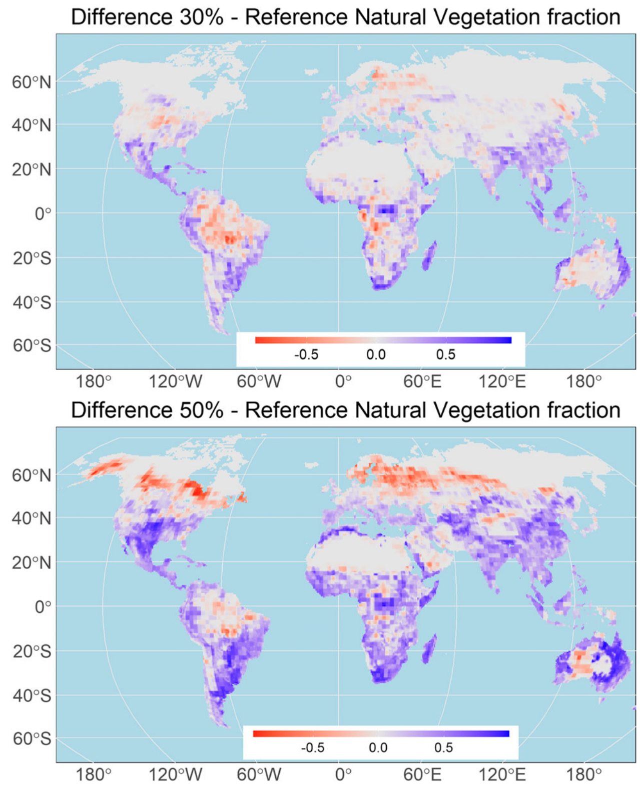

FIGURE 1 Differences in natural vegetation fractions between the 30% (top) and 50% (bottom) protection scenarios and the reference scenario averaged for 2056–2060.

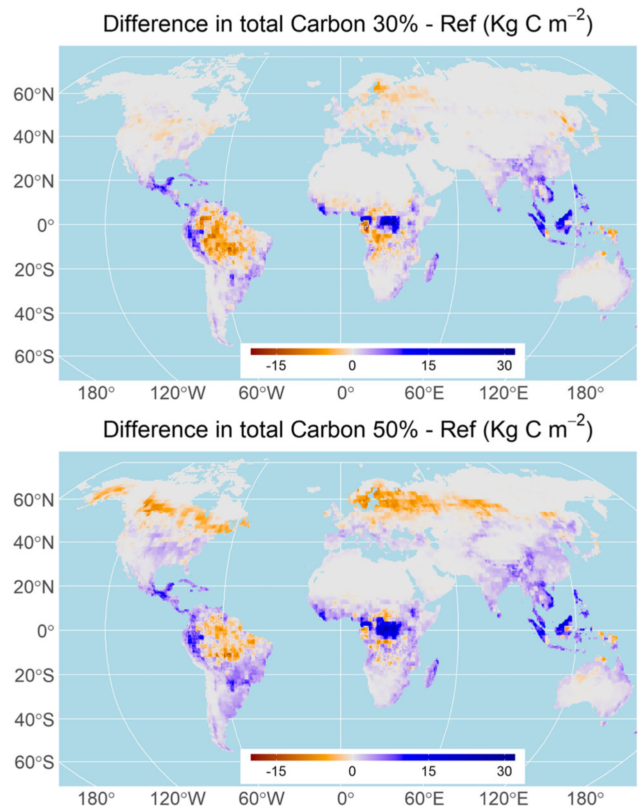

FIGURE 2 Differences in total carbon pools between the 30% (top) and 50% (bottom) protection scenarios and the reference scenario for 2056–2060.

change dynamics, with large regional increases and decreases in agricultural land, compared to the Reference (Figure 1).

At the end of the simulation period, both the 30% and the 50% protection scenarios showed an increase in natural vegetation across large parts of the globe, compared to the Reference, except in the northern latitudes. Agricultural expansion in the 30% scenario included parts of Africa, South America, north-eastern Europe and the US Agricultural expansion into northern latitudes was more prominent in the 50% scenario (Figure S3).

The simulated changes in the fractions of protected versus agricultural land (Figure 1, Figure S3) corresponded with the spatial patterns of gains and losses of total C (Figure 2) and vegetation C (Figure S4) pools computed with LPJ-GUESS, with increasing C pools in some tropical regions of South America, central Africa, southeast and southern Asia, and declining C pools in North America, Europe and some regions of the Amazon. These patterns were found for both protection scenarios, with stronger effects in the 50% scenario. They were dominated by vegetation C changes in response to deforestation and natural vegetation regrowth (Figure 2, Figure S4, Table 1).

In all three scenarios, the total C stored in global terrestrial ecosystems increased from around 1890 PgC at the beginning of the experiment to ∼1900 PgC in the reference scenario, ∼1950 PgC in the 30% scenario and 2000 PgC in the 50% scenario by 2060. A similar trend was found for vegetation C (Figure 3). Most global total C was stored in the northern band, while vegetation C was mainly stored in the tropics (Table 1).

The NPP in all three scenarios increased globally from present-day to the end of the simulations, although by smaller amounts in the northern band for the 50% scenario compared to the 30% scenario and the reference (Table 1). The interannual variation in NPP was highest for the southern band in all scenarios and for the northern band in the present-day (Table 1). The spatial patterns in NPP mirrored the changes found for agricultural areas and C pools. It was lower in regions of agricultural expansion (compared to the reference) and higher in newly protected areas (Figure 4). Although the global total NPP was slightly lower in the reference scenario, it was broadly similar in all three scenarios (between 65 and 67 PgC year^{-1}).

Land-use change to agriculture caused similar carbon losses across the three scenarios (96 PgC for reference scenario, 94 PgC for the 30% scenario and 89 PgC for the 50% scenario). However, in both protection scenarios, the expansion of agriculture occurred mainly in the northern band where, based on Noon et al. (2022), the total amount of irrecoverable C is approximately 101 PgC (Figure 5 and S6). In the tropical band, the risk of losing irrecoverable C (estimated as 132 PgC) was much lower since the expansion of protected areas resulted in higher total C pools in both protection scenarios (for instance, in the northern Andes, central Africa, Southeast Asia and northern China). In the southern band, the irrecoverable C risk is also

TABLE 1 Total carbon, vegetation carbon (PgC) and NPP (PgC year^{-1}) by latitude band for the present-day (averaged 2016–2020) and the end of the simulation (averaged 2056–2060) for each scenario. Coefficients of variation of NPP (%) for the five averaged years are shown in parenthesis.

	Latitude	Present	Reference	30%	50%
Total carbon	**South**	92	93	98	103
	Tropics	741	705	747	800
	North	1059	1102	1105	1098
	Global	**1892**	**1900**	**1950**	**2001**
Vegetation carbon	**South**	12	13	17	20
	Tropics	318	287	321	367
	North	120	154	156	150
	Global	**450**	**454**	**494**	**537**
Net primary production (NPP)	**South**	3.1 (8.7)	3.6 (8.3)	3.7 (10)	3.6 (12.3)
	Tropics	33.2 (3.3)	37.6 (2)	38.8 (2.5)	39.5 (2.9)
	North	20.9 (4.5)	24.2 (1)	24.2 (1)	23.8 (1.1)
	Global	**57.3 (2.1)**	**65.4 (1.5)**	**66.7 (1.9)**	**66.9 (2.1)**

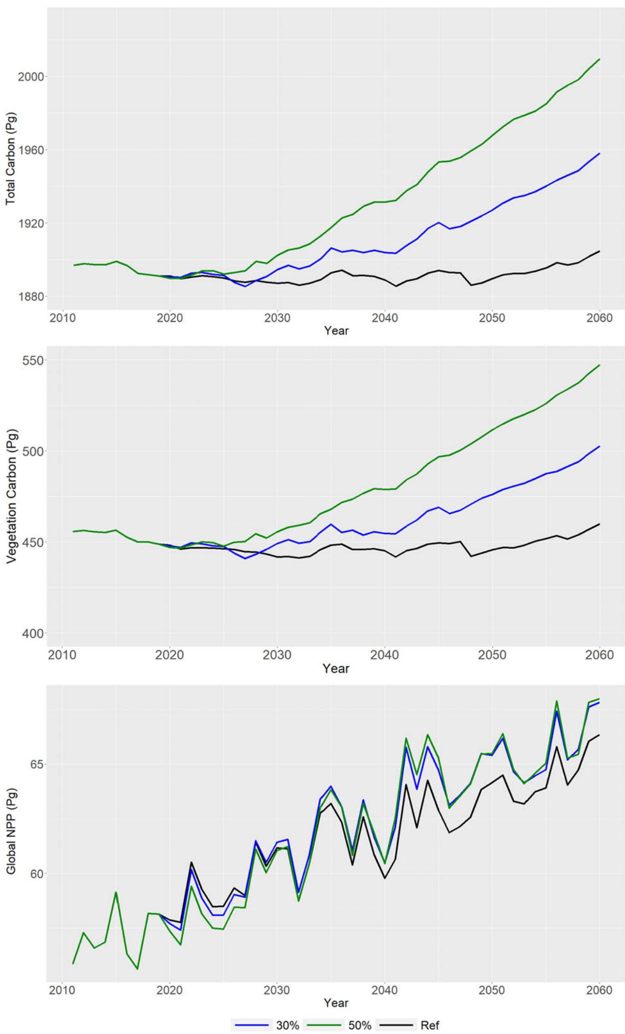

FIGURE 3 Time series of global total carbon (top) and vegetation carbon (bottom) for the reference scenario (ref), 30% and 50% protection scenarios. Note the difference on the y-axis scale for total and vegetation carbon.

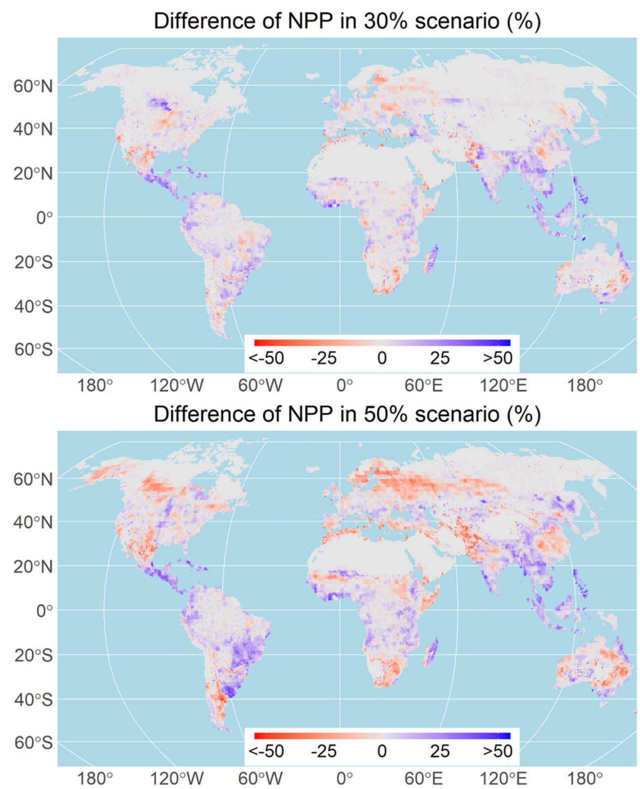

FIGURE 4 Difference of net primary production (NPP) for 30% (top) and 50% (bottom) protection scenarios minus the reference scenario, expressed as a percentage of the protection scenario value. Grid cells with NPP below 0.2 kgC m^{-2} were not considered to avoid abnormal percentage changes.

small (Table S1) due to the low amount of irrecoverable C in South America and Australia (13 PgC) and its limited spatial alignment with the areas of simulated agricultural expansion.

The relationship between irrecoverable C and total C difference (protection scenarios-reference) showed low spatial correlation

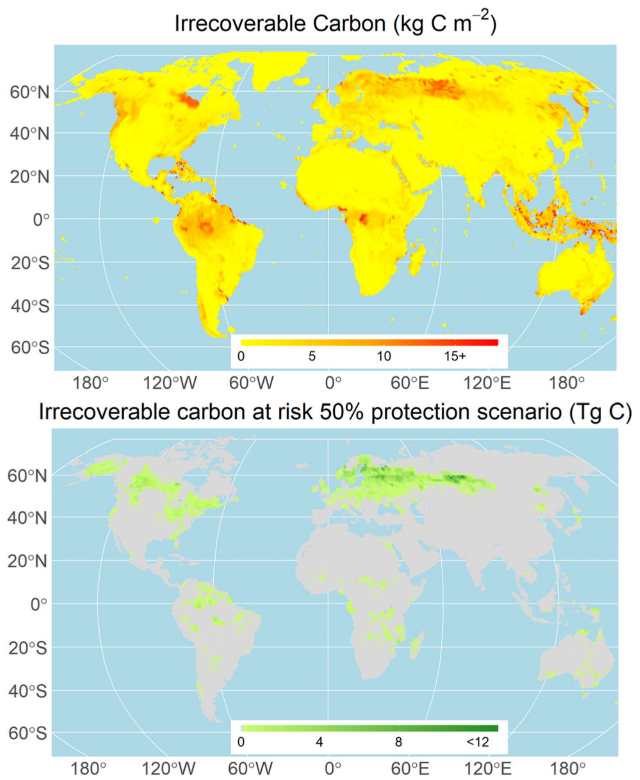

FIGURE 5 Total irrecoverable carbon estimated by Noon et al. (2022) (top) and irrecoverable carbon at risk (TgC per grid cell) in locations of agricultural expansion in PLUM simulations for the 50% protection scenario (bottom), grey colour shows locations without irrecoverable carbon at risk.

coefficients in the three latitude bands. Still, the relationship was negative in the northern band for both the 30% and 50% scenario, respectively ($\rho = -0.12$ *and* $\rho = -0.27$), and positive in the tropics ($\rho = 0.07$ and $\rho = 0.15$) and the southern band ($\rho = 0.12$ and $\rho = 0.14$). Consistently, bagplots in Figure S5 show that the northern band grid cells with higher values of irrecoverable C tend to have lower total C averaged for 2056–2060 in the 50% scenario compared to the reference. In the southern and tropical bands, most grid cells with high irrecoverable C showed a gain of total C.

The reference scenario showed a small expansion of cropland compared to the present-day, while in both protection scenarios, the global cropland area decreased, especially in the southern and tropical bands. In the northern band, both cropland and natural vegetation increased, leading to a 5% net increase in cropland in the 50% scenario (Table S2). Despite the reduction in cropland in the protection scenarios, the global crop production did not significantly change due to management intensification to enhance crop yields in the northern band (Table 2). N fertiliser input increased across all three scenarios and latitude bands compared to the present-day. However, in the 30% and 50% scenarios, the fertiliser input was lower in the southern and tropical bands compared to the reference. A similar pattern was observed regarding the amount of water for irrigation. In the northern band, agricultural expansion and intensification in protection scenarios led to a higher application of fertiliser and irrigation water. Specifically, in the 50% protection scenario, the use of nitrogen fertiliser was 50% higher, and irrigation water use was 58% higher compared to present-day levels, while the reference scenario had increases of 12% and 19%, respectively (Table 2).

TABLE 2 Changes by latitude band (averaged 2056–2060) of nitrogen fertiliser applied, irrigated water and total crop production. All expressed as percentage of change to the present-day (averaged 2016–2020).

	Latitude	Reference	30%	50%
N fertiliser applied	South	59	56	52
	Tropics	60	52	25
	North	12	16	50
	Global	31	30	42
Irrigation water	South	124	92	23
	Tropics	59	23	−14
	North	19	43	58
	Global	44	39	26
Crop production	South	26	19	−23
	Tropics	11	−8	−30
	North	12	12	27
	Global	13	2	−5

4 | DISCUSSION

A large part of the current land carbon sink, which removes 25%–30% of anthropogenic carbon emissions each year, is located in natural and seminatural ecosystems (Ahlström et al., 2015; Friedlingstein et al., 2023), emphasising the critical need to avoid further losses of these ecosystems for climate change mitigation. Our results provide further evidence in that regard, as the combined effects of climate change, increasing atmospheric CO_2 and land-use change in the reference scenario resulted in little change in global C pools compared to present-day. In contrast, in both protection scenarios, vegetation C increased notably, although the simultaneous losses from agricultural expansion were similar across the three scenarios. By 2060, the projected increase in stored carbon within terrestrial ecosystems is estimated to be around 60 PgC for the 30% scenario and 110 PgC for the 50% scenario. This represents a significant contribution to climate change mitigation, equivalent to 6–10 years of global anthropogenic CO_2-C emissions, which averaged 10.9 ± 0.8 PgC year^{-1} from 2013 to 2022 (Friedlingstein et al., 2023).

Our findings match previous reports that afforestation and reforestation are cost-effective climate change mitigation options (Fuss et al., 2018). In some mitigation scenarios, projected future forest carbon uptake rates are up to an additional ca 3 PgC year^{-1} (Roe et al., 2019). This would double the current total global carbon sink on land, but, resonating with the 30%–50% strict protection explored in this study, it would also require millions of hectares of agricultural land to be transformed into forests (Fuss et al., 2018;

Popp et al., 2017). Growing demands for food, fibre, energy and the increasing dependence on ecosystems for climate change mitigation make the use of land a challenge (Erb et al., 2016). Bayer et al. (2023) argued that increased crop production, C storage and freshwater availability could be achieved under future climate change scenarios by optimally allocating land globally and suggested benefits for biodiversity and natural vegetation in tropical regions but noted continued loss in temperate zones where, as in our study, food production was concentrated. However, that study did not consider the risk of irrecoverable C loss in these areas.

Another study estimated that the protection of 44% of land could meet global targets for biodiversity conservation and ecosystem service provision, but 37% of the identified area overlapped with zones of high economic potential for food and/or energy, mainly in northern temperate regions (Neugarten et al., 2024). Jung et al. (2021) found that protecting 30% and 50% of the land surface could preserve 60% and 85% of total C stocks, respectively, while also considering a clean freshwater supply and minimising the number of threatened species. However, their study did not consider climate change impacts on ecosystems or food production as a constraint. These studies, along with ours, are indicative of the potential co-benefits of protecting and restoring ecosystems on the C cycle and biodiversity but also of the multiple conflicts arising from diverse demands on land, which vary greatly depending on the scenario explored.

The spatial relationship between what has been labelled irrecoverable C and agricultural expansion, particularly in the 50% protection scenario and northern latitudes, highlights how C is at risk due to land-use change leading to further C emissions, local biodiversity loss and impacts on other ecosystem services (Goldstein et al., 2020; Noon et al., 2022). Our results underpin arguments for careful and equitable distribution of protected areas under the goals of the CBD, seeking—among others—the co-benefits of aligning protected areas with climate change mitigation goals.

Climate change-related weather extremes add considerable uncertainty to our projections. For instance, heat, drought, wildfires and insect outbreaks reduce productivity and carbon sink capacity and increase mortality in natural and managed ecosystems (Anderegg et al., 2022; Helman & Bonfil, 2022). LPJ-GUESS simulates some of these impacts, such as wildfires, high temperatures and drought effects (Knorr et al., 2016; Schauberger et al., 2017). However, other extreme weather impacts are represented as a subsumed stochastically recurring disturbance that destroys patches on average every 100 years (Smith et al., 2014). This approach does not account for the high spatial variation in the return intervals of these disturbance events (Pugh et al., 2019), which additionally are expected to become more frequent with climate change (Anderegg et al., 2022). Therefore, it is challenging to assess whether LPJ-GUESS under or overestimates carbon uptake and losses from disturbance events.

In the northern band, the expansion of agriculture in the 50% protection scenario caused NPP to decline compared to the other two scenarios, in contrast to the NPP increase in the tropics. This response was expected since a lower NPP from cropland has been reported compared to forest, in addition to the removal of crop biomass during harvest (Gao et al., 2004; Medková et al., 2017; Pan et al., 2021). Moreover, the increase in fertiliser application rates due to cropland-use intensification would lead into higher nitrogen losses (Olin et al., 2015; Rabin et al., 2020). LPJ-GUESS does not differentiate between gaseous and water-dissolved losses, but either way, these losses would be expected to contribute to greenhouse gas emissions (as N_2O) or water or air pollution (via NO_3^- or NH_3). Increased fertiliser application would also generate additional GHG emissions through production, offsetting the co-benefit of enhanced C storage in protection scenarios. Fertiliser production is energy-intensive, accounting for approximately 45% of the total energy required in crop production, with estimated emissions ranging from 1.3 to 5.5 kg CO_2-eq./kg of N, excluding transportation and storage emissions (Walling & Vaneeckhaute, 2020). Similarly, intensification of irrigation would also generate GHG emissions directly related to the amount of pumped water. In the United States, emissions from irrigated croplands varied from 239 kg CO_2e ha^{-1} for soybean to 970 kg CO_2e ha^{-1} for sorghum (Driscoll et al., 2024). The concentration of agricultural production in northern latitudes would also increase GHG emissions from international processing, packaging, transport and distribution (Bayer et al., 2023; Michalský & Hooda, 2015), which represent around 15% of total food system emissions (Crippa et al., 2021).

The shift in agricultural production towards northern latitudes (Table S2), mainly under the 50% protection scenario, will contribute to a reduction in global food supply given the increasing demand, particularly in tropical and southern latitudes (Table 2). Henry et al. (2022), using the same land-use scenarios, highlighted the net-negative impacts of strict conservation measures on food provisioning due to declining cropland area, reducing food production, increasing food prices and the shift in diets towards less nutritional food and causing around 5 million of additional deaths by 2060. Higher yields in response to intensification could potentially offset some of these effects but would still harm consumers with higher prices. Incidentally, some of the agricultural expansion observed in Figure 1, for instance, in northern Finland or Alaska, may be overestimated because the version of LPJ-GUESS used in LandSyMM does not account for permafrost, and its influence on simulated productivity and infrastructure development such as road networks, which are not explicitly simulated in LandSyMM but assumed to be built in areas with sufficiently high productivity (Bayer et al., 2023; Henry et al., 2022).

Strategies can be developed to reduce agricultural expansion and its impacts, such as reducing yield gaps through increasing crop productivity and technological advancement, expanding agriculture into already converted or degraded areas or limiting other demands on land, such as bioenergy and urban expansion (Alexander et al., 2018; Arneth et al., 2023; Bayer et al., 2023; Henry et al., 2022). However, the fundamental challenge of land being a finite resource can only be addressed by altering patterns of food consumption, such as meat-based diets, and reducing food waste and overconsumption (Alexander et al., 2017; Erb et al., 2016).

Protected areas can impact human well-being both positively and negatively. In low-intensity anthromes like those often managed by indigenous people, sustainable relationships with biodiversity and landscape conservation have been observed (Ellis et al., 2021; Garnett et al., 2018). However, conservation planning frameworks often prioritise large areas of land for biodiversity restoration with little consideration for equity and land-use needs of local communities (Venier-Cambron et al., 2023). Strict restrictions on local communities to access natural resources or relocating them for conservation can threaten livelihoods and raise concerns about socioeconomic equity and justice, especially when conservation prioritisation, as in this study, disproportionately focuses on the global south (Jones et al., 2020; Naidoo et al., 2019; Palomo et al., 2014).

Lowering protection strictness to facilitate access to wild foods, recreation and limited agriculture or forestry could alleviate these negative societal impacts and increase acceptance of protected areas, though it may result in trade-offs with C storage and biodiversity goals (Arneth et al., 2023). However, prioritisation approaches for conservation and C storage impacts often insufficiently represent the socio-institutional factors critical to land-use decisions such as regional land tenure systems and indigenous rights and needs (Baragwanath et al., 2023; Venier-Cambron et al., 2023). Integrating shared multifunctional areas that are important for land-dependent communities could result in more equitable conservation prioritisations (Venier-Cambron et al., 2024). For example, indigenous territories in the Brazilian Amazon with secure land tenure and collective property rights experience lower deforestation rates and higher secondary forest growth compared to other areas (Baragwanath et al., 2023; Baragwanath & Bayi, 2020).

The implementation of large-scale conservation that spans across national borders is also challenged by geopolitics that were not captured in LandSyMM prioritised 30% and 50% scenarios. Here, it was assumed that strict protection across large areas of the land surface would be achieved; however, political and economic differences between nations can obstruct conservation efforts (Hodgetts et al., 2019). Geopolitical characteristics of nations can dictate the establishment of new protected areas, particularly when competing states, communities or institutions dispute conservation zones (Hodgetts et al., 2019). Geopolitical issues can also hamper the efficiency of conservation efforts if access for conservation practitioners is prohibited or the movement of wildlife and local communities is opposed. Future modelling work could examine the influence of geopolitical events with regard to the likelihood and ethics of establishing protected areas.

5 | CONCLUSIONS

Strategies for global and regional land use that aim to protect biodiversity, such as the CBD goals and climate change mitigation, require consideration of the trade-offs for carbon cycling and storage. This involves identifying interactions and conflicts from the extension of protected land areas, ensuring food security and accommodating other economic and nonmaterial land uses. Our study highlights some of the conflicts between conservation objectives and the potential for agriculture expansion, particularly in northern temperate regions with irrecoverable carbon from a decadal perspective.

Our findings reinforce that increasing protected areas can have positive and negative impacts across the carbon cycle, ecosystem services and human well-being, demanding careful consideration of access rights and societal impacts. Addressing these complex trade-offs requires not only innovative strategies such as increasing agriculture productivity to spare land for protection but also fundamental shifts in food and energy consumption patterns, as well as land-use priorities to ensure sustainable resource management for future generations.

AUTHOR CONTRIBUTIONS

Almut Arneth and Mark Rounsevell developed the idea. Hector Camargo-Alvarez, Daniel Bampoh and Sam Rabin performed the LPJ-GUESS model runs and analysed the data. Hector Camargo-Alvarez, Daniel Bampoh, Valeria Mazzola and Almut Arneth wrote the first draft. Peter Alexander, and Roslyn Henry performed PLUM runs. All authors contributed to discussing results, editing and reviewing the final manuscript.

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CONFLICT OF INTEREST STATEMENT

Authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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