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Abstract

Conserving biodiversity while mitigating climate change is one of the defining sustainability challenges of this century. Paris-aligned mitigation pathways rely heavily on forest restoration and bioenergy with carbon capture and storage (BECCS). While forest restoration can simultaneously enhance wildlife habitat and increase carbon sequestration, large-scale biomass production for BECCS may intensify land competition and conflict with biodiversity conservation goals. Here, we use an interlinked land-use (MAgPIE), energy (MESSAGE*ix*), and climate (MAGICC) modeling framework to explore the synergies and trade-offs between biodiversity conservation and climate mitigation. We find that sustainable bioenergy potential compatible with ambitious biodiversity conservation targets is below 100 EJ/yr, limiting late-century carbon removal through BECCS in 2 °C scenarios to less than 6 $GtCO_2$/yr. At the same time, ambitious biodiversity conservation can approximately double carbon sequestration in forest systems. Our results show that Paris temperature goals remain achievable under ambitious biodiversity targets and that peak temperatures are lowered as much as 0.2°C compared to Paris-aligned scenarios without biodiversity targets, although doing so requires earlier and more stringent decarbonization.

Introduction

The three Rio Conventions are rooted in the integrated approach to sustainable development articulated in *Agenda 21* and the *Rio Declaration on Environment and Development*, emphasizing the interdependence of environmental challenges (Viñuales 2015). Under the UNFCCC, the Paris Agreement defines the goal to stay well below 2 °C of global warming (UNFCCC 2015), which necessitates achieving net-zero greenhouse gas emissions as soon as possible and net carbon dioxide removal (CDR) thereafter. CDR emerges as especially important in overshoot scenarios (IPCC 2023b, Riahi *et al* 2021). Among the major land-based CDR options are afforestation and reforestation, bioenergy with carbon capture and storage (BECCS), and biochar (Pilli *et al* 2024).

The Kunming-Montreal Global Biodiversity Framework under the CBD foresees to "halt and reverse biodiversity loss" in its Mission 2030 statement (UNEP 2022), highlighting the global importance of biodiversity recovery (IPBES *et al* 2019, Rockström *et al* 2023, Pörtner *et al* 2021). A primary driver of biodiversity loss is the conversion of intact habitats (Rockström *et al* 2023, Hirata *et al* 2024, Núñez-Regueiro *et al* 2021, Van Vuuren *et al* 2010, Immerzeel *et al* 2014). Thus, these aspirations are at odds with envisaged land-based climate mitigation efforts under the Paris Agreement (Wu *et al* 2019, Frank *et al* 2021). In many Paris Agreement-compatible scenarios, BECCS plays a major mitigation role (IPCC 2023b), often requiring extensive expansion of agricultural land for bioenergy crops, which can hamper biodiversity conservation (Wu *et al* 2019, Frank *et al* 2021, Braun *et al* 2025, Hanssen *et al* 2022). Stricter biodiversity conservation, in turn, limits cropland expansion for BECCS and thus its mitigation potential. At the same time, it may bolster natural carbon sinks (Pörtner *et al* 2021, Shin *et al* 2022, Gorman *et al* 2023).

It is thus essential to assess climate mitigation and biodiversity conservation scenarios in a common framework to understand where these different goals might support or hinder each other and how they can be balanced sustainably. Such

interlinkages have so far rarely been considered in policy discussions and integrated assessments (Rockström *et al* 2023, Pörtner *et al* 2021, Hirata *et al* 2024, Van Vuuren *et al* 2010, de Lamo *et al* 2020, Prütz *et al* 2026).

To close this gap, we conduct a systematic scenario assessment of bioenergy supply, alternative land-use activities for climate mitigation, and biodiversity-enhancing land-use strategies. By running scenarios in an interlinked land-use and energy system constrained by varying biodiversity intactness targets, a diverse set of climate-biodiversity narratives can be assessed, including business-as-usual biodiversity conservation with nearly unconstrained BECCS expansion as well as a strong focus on biodiversity conservation and natural carbon sinks.

Methods

The MAgPIE-MESSAGE*ix* linkage

We utilize a newly implemented integrated assessment framework comprising a detailed biophysical model of the land-use sector (the Model of Agricultural Production and its Impact on the Environment (MAgPIE (Dietrich *et al* 2019)), and a bottom-up systems engineering model of the energy-economic system (the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE*ix* (Huppmann *et al* 2019)). The two models are integrated via a MAgPIE land-use emulator implemented into MESSAGE*ix* (Figure 1). The emulator entails a large ensemble of MAgPIE scenarios under alternative drivers, namely bioenergy supply responses to different bioenergy price incentives and land-based mitigation responses to varying climate policy stringencies, i.e., GHG prices on land-use activities. The emulator is then added to MESSAGE*ix* as dynamic vectors, representing internally consistent land-use transitions given specific GHG prices and bioenergy demands, enabling endogenous representation of land-use consequences of bioenergy use in MESSAGE*ix* by blending different MAgPIE scenarios over time. Specific equations ensure that the path-dependency of land-use transitions are retained. See also supplementary information section S.1.

For the scenario solution space, we utilize matrices comprising 84 bioenergy-carbon price combinations. Bioenergy production levels are modeled for seven global price incentive scenarios starting from 0 US$2005/GJ in 2020, linearly increasing to their targets of 0–45 US$2005/GJ in 2100. For each of these production scenarios, twelve global carbon prices are introduced (0–103 US$2005/t CO_2 in 2025, discounted at 5 % per year to 0–4000US$2005/t CO_2 in 2100. Underlying demands (e.g., food) are based on SSP2 input data.

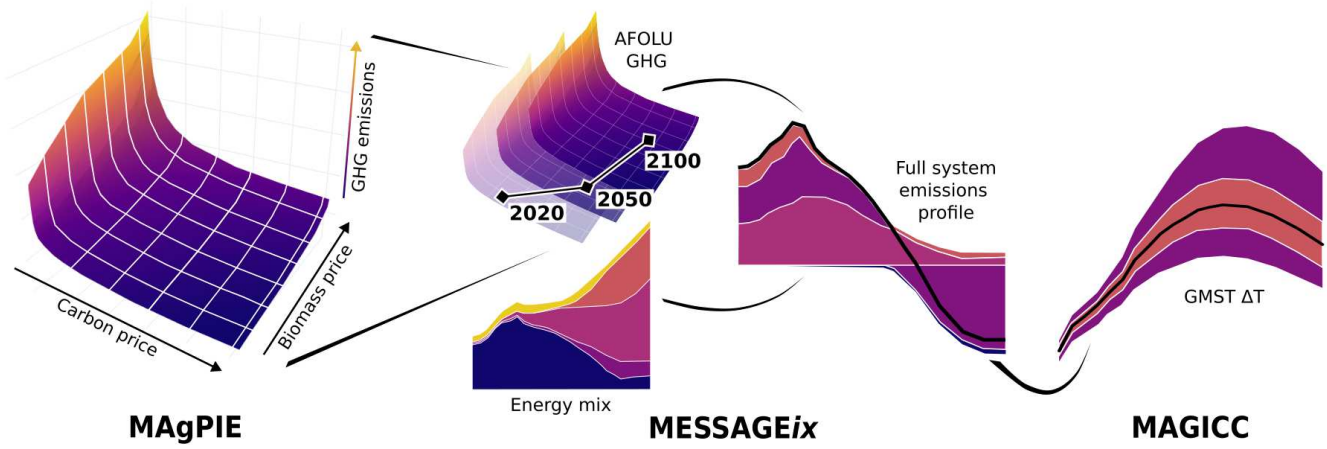

Figure 1. Conceptual implementation of MAgPIE land-use emulator in MESSAGE*ix* and its link to MAGICC. Left: A set of carbon-biomass price combinations are solved in MAgPIE to create a scenario matrix to be implemented into MESSAGE*ix* as land-use emulator. Alongside the resulting land-use emissions and biomass potentials, various indicators such as land-use change and biodiversity intactness are stored for each bioenergy-carbon price scenario. The combination of all such scenarios creates a solution space for each time step and every stored variable, as shown here for global land-use GHG emissions in 2100. Center: As part of its optimization process, MESSAGE*ix* creates a new virtual land-use scenario within the solution space by linearly combining the scenarios provided to the emulator. The resulting biomass and emissions constrain the energy mix and contribute to the system's total emissions, and other land-use indicators are used as emulator constraints or reporting variables. Right: Finally, the GHG emissions from the optimized MESSAGE*ix* solution, including the land-use emissions provided through the MAgPIE emulator, are fed into MAGICC to model their impact on the global climate.

Scenarios for biodiversity and climate protection

To explore the nexus of biodiversity conservation and climate mitigation, we employ a systematic scenario analysis investigating policy sets of various ambition regarding both targets. For each biodiversity scenario, we create a land-use

emulator matrix, as described above and shown in Figure 1. Their setup varies in their biome-specific biodiversity conservation target, summarized in Table 1.

Table 1. Biodiversity conservation and climate policy scenarios. Biodiversity conservation ambition primarily varies in the targeted minimum Biodiversity Intactness Index (BII) by 2100 per biome and region, with no minimum in the Baseline. The BII expresses the ratio of biodiversity abundance compared to a theoretical maximum (Scholes and Biggs 2005). As the minimum alone only enforces a gradual increase in biodiversity-rich land types, an ambitious BII target may lead to production shifts from low-BII regions to regions starting at BIIs higher than the minimum. To avoid increasing biodiversity conservation ambition leading to a loss of biodiversity in high-BII regions, scenarios above the baseline include a "no-loss" setting. Further, ambition beyond the baseline includes strict protection of additional land areas, defined as biodiversity hotspots (IUCN and UNEP-WCMC 2020). The climate policy stringency is defined by the applied carbon price, implemented from 2025 starting values between 0 and 103 US$2005/t CO_2 at 5 % annual discounting.

Biodiversity Conservation

	Baseline	**Low Ambition**	**Medium Ambition**	**High Ambition**
Target Minimum BII	No Target	0.7	0.74	0.78
Protected Area	WDPA	WDPA + Biodiversity Hotspots	WDPA + Biodiversity Hotspots	WDPA + Biodiversity Hotspots

Climate Policy

	Baseline	**Low Stringency**	**Medium Stringency**	**High Stringency**
Carbon Price in 2100	0 US$2005 / t CO_2	50 US$2005 / t CO_2	400 US$2005 / t CO_2	4000 US$2005 / t CO_2

Biodiversity conservation is quantified by the Biodiversity Intactness Index (BII), an indicator of intermediate complexity that is commonly used for biosphere integrity (Steffen *et al* 2015). It represents the abundance of biodiversity in a biome as ratio relative to the theoretical maximum (Scholes and Biggs 2005). A BII of 1, for example, indicates the theoretical maximum that is achieved within intact habitats derived using a space-for-time approach. In turn, a 0.02 drop in BII corresponds to losing all species across 2 % of previously undisturbed land. In our scenarios, BII targets range from the targetless *baseline* (implying continued loss over time) to *high ambition* conservation targeting 0.78 per Biome, corresponding to "bending the curve" of biodiversity loss (Leclère *et al* 2020) by increasing global BII over time and balancing out 21st century losses. To create logically consistent scenarios, conservation ambition beyond the *baseline* is further expressed through area-based conservation policies protecting biodiversity hotspots (Myers *et al* 2000). By comparison, the *baseline* scenario is limited to current protected areas as defined by the World Database on Protected Areas (WDPA) (IUCN and UNEP-WCMC 2020). Further, to avoid conservation scenarios above *baseline ambition* reducing biodiversity in biomes with a BII above the target by shifting production there, biome-specific BIIs are not allowed to drop below 2020 levels in these scenarios. Such drops would incorrectly imply that a BII increase in one biome can balance out the loss in another, but biomes are unique and cannot be directly compared.

To better understand possible shortcomings of this BII approach, we quantify the potential displacement of natural and extensive land by forest expansion on the spatial scale. We define displacement as the minimum of forest gain and natural land loss, ensuring a conservative estimate that cannot exceed either quantity. To explore the results' sensitivity to different definitions of natural land, we apply three cell-level co-occurrence methods to the MAgPIE 0.5° gridded output. See also supplementary material (Tables SI.2-1–SI.2-3).

The climate policy dimension in the land-use scenarios is defined through the stringency of the carbon price trajectory. They range from the *baseline stringency* with no carbon price to the *high stringency* scenario, starting from 103 US$2005/t CO_2 in 2025. These increasing prices affect the price competitiveness of land-use changes and thus result in shifting land-use patterns, foremost avoided deforestation and increased re/afforestation, and increased land-use intensity.

First, we develop a set of scenarios to understand how climate policies in the land sectors (forest and agriculture) affect biodiversity conservation. These scenarios assume *baseline ambition* for biodiversity conservation in combination with different climate policy stringencies. In this setup, we analyze four scenarios across the full range of modelled carbon prices, looking at their impact on land use and BII. The focus is on land-based policies, so bioenergy demand is kept at baseline levels.

Second, we investigate fully coupled scenarios with competition for land also considering bioenergy. In these scenarios, we assume various biodiversity conservation efforts and climate mitigation policy stringencies to fully integrate both policy objectives: All four biodiversity scenario matrices are solved in MESSAGE*ix* under various full-century carbon budgets, i.e., net emissions in the optimization period 2025–2100, to obtain cost-effective land-use transitions as well as energy supply and demand trajectories. The investigated budgets range from 300 to 1,000 Gt cumulative CO_2 emissions, equating climate

scenarios in line with a high likelihood to stay below 1.5 and 2 degrees warming, respectively (IPCC 2023a). We analyze integrated system indicators, such as the energy mix, land-use and emissions profiles, and use the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) (Meinshausen *et al* 2011) to assess resulting peak and long-term global surface air temperature (GSAT), i.e., the weighted average of near-surface air temperatures over land, oceans, and sea ice (IPCC 2023a).

Results

The impact of climate policy on biodiversity in the land-use sector

In this section, we isolate the effects that climate change mitigation policies acting on the land-use sector have on biodiversity, deliberately excluding any additional land demand for biomass production by keeping biomass demand at baseline levels. This stylized setup allows us to disentangle the direct effects of land-based climate policies—such as avoided deforestation, re/afforestation, and changes in agricultural management—from indirect effects driven by competition for land between food production, ecosystems, and bioenergy. The implications of expanding bioenergy demand are examined in the subsequent section.

To assess the biodiversity implications of land-based climate mitigation, we analyze a representative set of mitigation scenarios from the *baseline* biodiversity conservation matrix (Figure 2). The land-use responses to increasing climate policy stringency result in cumulative land-sector CO_2 emissions of 345 (*baseline*), 146 (*low stringency*), 55 (m*edium stringency*), and -108 (*high stringency*) $GtCO_2$ by 2100, respectively (Figure 2A). Higher carbon prices incentivize both avoided deforestation and increased re/afforestation, enhancing natural carbon storage, particularly in forest ecosystems.

These mitigation-driven land-use adjustments are accompanied by a spatial reallocation of agricultural production toward regions with lower carbon opportunity costs. Further, rising carbon prices make agricultural intensification more cost-effective, leading to higher yields on existing cropland. As a result, global pasture and cropland areas contract over time, while forests and other natural land expand (Figure 2C). Quantitatively, in the *High Stringency* scenario, cropland and pasture areas decline by approximately 10 % and 20 %, respectively, relative to 2020 levels.

This results in co-benefits for biodiversity. By protecting and expanding high-carbon natural ecosystems, climate policies lead to a globally increasing BII (Figure 2B). Under the *high stringency* scenario, the historical decline in global BII is halted shortly after policy implementation and subsequently reversed, with biodiversity recovering toward, and eventually exceeding, mid-1990s levels. This reflects large-scale rewilding driven by sustained incentives for natural land expansion.

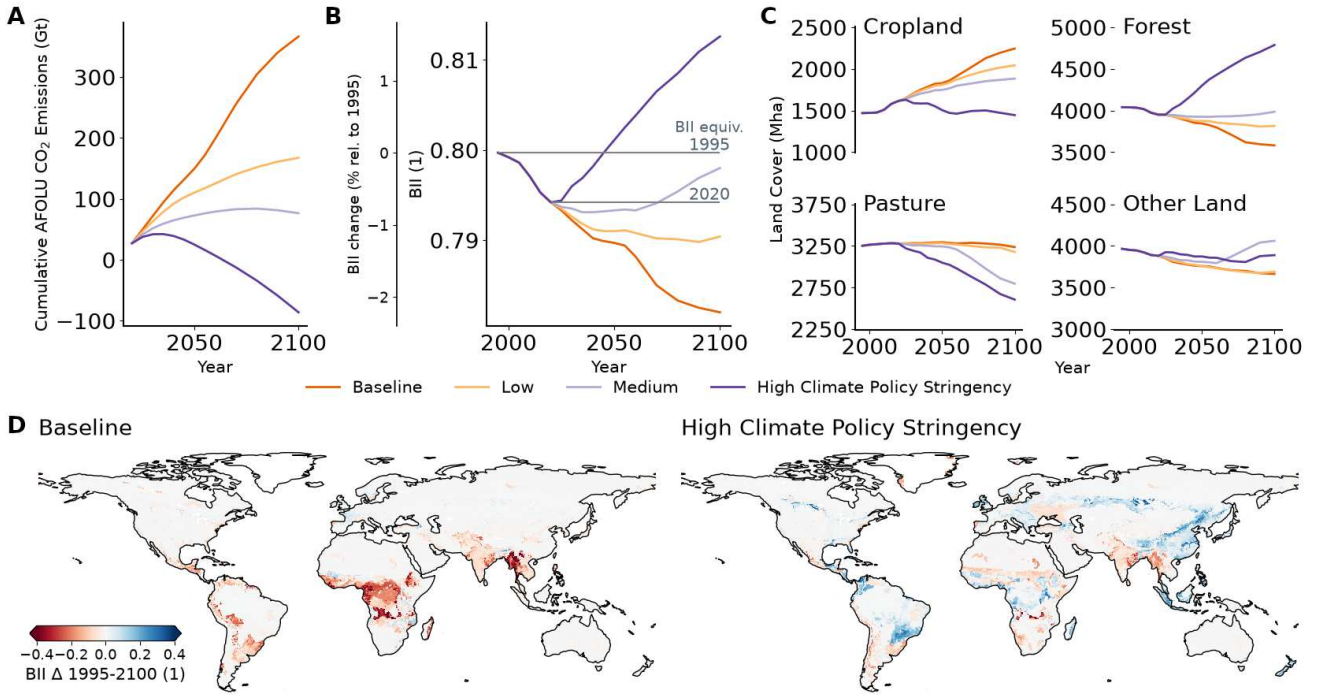

Figure 2. The impact of climate policy on biodiversity and land-use change. Top row: Cumulative land-use CO_2 emissions trajectories in four modeled climate change mitigation scenarios (A), associated changes in globally aggregated BII (B), and associated change in cropland, forest, pasture, and other natural land (C). Bottom row: Disaggregated local changes in BII between years 1995 and 2100 in the Baseline and High climate policy stringency scenario.

Biodiversity gains are especially pronounced in tropical rainforest regions such as the Congo basin and South-East Asia, where avoided deforestation and forest regrowth deliver substantial carbon and biodiversity benefits. In contrast, some lower-carbon or intensively managed regions experience localized declines in BII in the *high stringency* scenario, as agricultural production is displaced toward these areas in the absence of explicit biodiversity conservation policies (Figure 2D).

Even moderate climate policy stringencies yield noticeable biodiversity benefits. The *low stringency* scenario avoids over 60 % of the BII loss observed in the *baseline*, while the *medium stringency* scenario stabilizes global BII by mid-century before gradually recovering, reaching 2020 levels by 2070. Without climate policy, by contrast, rising food demand combined with limited incentives for intensification drives continued cropland and pasture expansion into biodiversity-rich regions, causing continuous declines in BII, particularly in the Congo basin, India, and Southeast Asia, as well as across South America (Figure 2D).

Overall, these results indicate that land-based climate mitigation policies alone can generate substantial biodiversity co-benefits, while also highlighting that, in the absence of dedicated biodiversity safeguards, such policies may redistribute biodiversity pressures across regions rather than fully eliminating them.

Sustainable biomass use aligned with biodiversity conservation

While the results so far indicate potentially substantial co-benefits for biodiversity from climate mitigation policies, they do not account for competition over land arising from bioenergy production, which plays a central role in many climate mitigation pathways. Increasing bioenergy demand can fundamentally change land-use dynamics, potentially offsetting biodiversity gains from avoided deforestation and natural land expansion.

We therefore extend the analysis to explicitly consider increasing demand for bioenergy and assess how different levels of biodiversity conservation ambition constrain the sustainable supply of bioenergy. This allows us to quantify the extent to which bioenergy production can be scaled without compromising biodiversity objectives and to identify the resulting trade-offs between bioenergy-based mitigation and ecosystem conservation.

We find that in the absence of biodiversity conservation beyond the WDPA baseline, the global techno-economic bioenergy potential is very large, exceeding 600 EJ/yr by 2100 (Figure 3A), a level comparable to today's total global primary energy demand (Energy Institute 2024). However, this would require widespread cropland expansion, entailing severe biodiversity losses. As soon as biodiversity conservation policies are introduced, the bioenergy potential declines sharply. Even the *low ambition* "stop biodiversity loss" scenario, which stabilizes BII around 2020 levels, reduces the bioenergy potential by more than half.

Under the most ambitious biodiversity conservation scenarios, the bioenergy potential falls to approximately 100 EJ/yr by 2100, corresponding to roughly 15% of the techno-economic potential. This level is substantially lower than the average bioenergy deployment in stringent mitigation scenarios assessed in IPCC AR6 that rely heavily on BECCS (Byers *et al* 2022). From a spatial perspective, this sustainable level of bioenergy production is concentrated in specific regions where biodiversity trade-offs are relatively small, while large-scale global expansion of bioenergy crops is avoided (Figure 3C).

Stronger biodiversity conservation also leads to pronounced changes in land-use patterns. Cropland and pasture areas contract substantially, while forest and other natural land expand by more than 50 % between 2020 and 2100 (Figure 3B). This creates a dual effect: Biodiversity conservation limits the potential for bioenergy production and associated negative emissions from BECCS but simultaneously enhances the natural carbon sink by reducing deforestation and promoting ecosystem recovery.

Overall, these results demonstrate that biodiversity conservation fundamentally reshapes the role of bioenergy in climate mitigation strategies. While bioenergy remains a potentially important component of the mitigation portfolio, its large-scale deployment is incompatible with ambitious biodiversity conservation goals. This highlights the need to assess climate mitigation pathways within an integrated land-energy framework that explicitly accounts for ecological constraints.

Full integration of climate and biodiversity ambitions across the energy and land sector

Thus, we explore characteristics of energy and land transitions that consider integrated biodiversity and climate policy targets. To disentangle the effect of the biodiversity target, we systematically vary the biodiversity conservation ambition from the *baseline* to *low*, *medium,* and *high*. We combine these biodiversity conservation ambitions with a cumulative full-century CO_2 budget of 1,000 $GtCO_2$, consistent with limiting global warming to below 2°C (IPCC 2023a).

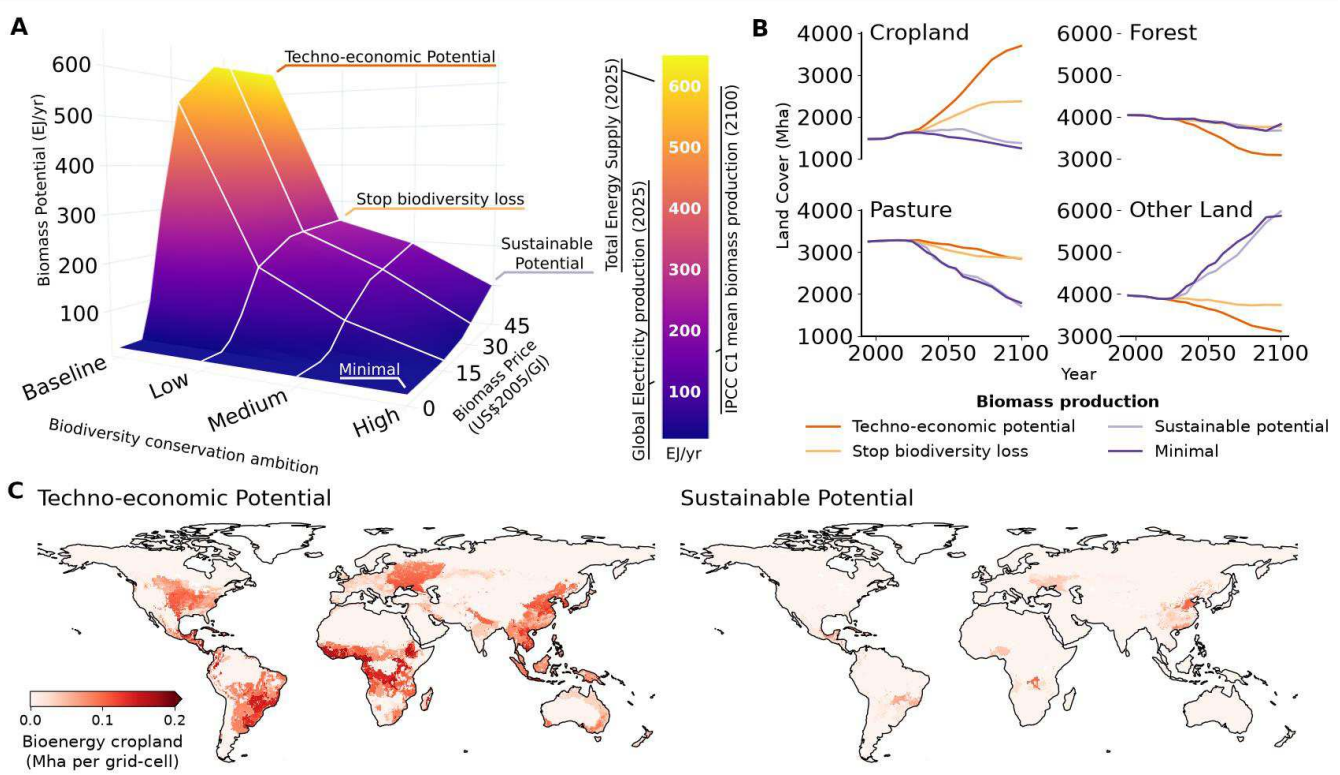

Figure 3. The impact of biodiversity policies on bioenergy availability and land-use change. Top row: Bioenergy potentials in 2100 dependent on biodiversity conservation ambition, expressed through target minimum biome-specific biodiversity intactness index, (A) and associated changes in cropland, forest, pasture and other natural land (B). "Techno-economic potential" marks a hypothetical bioenergy potential without considering biodiversity, "Stop biodiversity loss" marks the potential for a low BII target combined with a general BII loss prohibition policy after 2020, and "Sustainable" and "Minimal" production are associated with a high-ambition biodiversity scenario at different bioenergy price levels. Bottom row: Disaggregated bioenergy production for techno-economic and sustainable potential.

We find that higher conservation ambition significantly affects both the energy portfolio mix and the timing of mitigation options (Figure 4). The more limited and thus more expensive bioenergy supply incentivizes a more rapid upscaling of other renewable energy sources, such as solar and wind, increasing the system's flexibility and reducing its dependence on bioenergy towards the latter half of the century. Further, ambitious biodiversity policies lead to an earlier and more aggressive phase-out of fossil fuels and more stringent near-term emissions reductions, both of which serve to reduce reliance on BECCS-driven mitigation due to its limited availability.

The share of forests and other natural land increases at higher levels of biodiversity conservation and doubles the forest carbon sink to about 2.6 $GtCO_2$/yr by 2100 compared to baseline biodiversity conservation ambition (Figure 5). Negative emissions through BECCS are at the same time reduced to about 5.9 $GtCO_2$/yr by 2100 under a *high ambition* biodiversity conservation. Overall, a sustainable climate transition which prioritizes biodiversity reduces emissions sooner and minimizes the reliance on BECCS in the long-term.

For the same carbon budget, biodiversity conservation reduces peak warming

To assess how biodiversity conservation affects temperature outcomes, we process MESSAGE*ix* emissions pathways through the simple climate model MAGICC to derive probabilistic global temperature trajectories.

For a given full-century carbon budget, biodiversity conservation leads to lower peak temperatures. For example, for 1,000 $GtCO_2$, *baseline* biodiversity conservation reaches a median peak warming of around 2.0 °C, compared to about 1.8 °C under *high ambition* (Figure 6). In addition, the *high ambition* scenario has an approximately 75 % probability of remaining below 2 °C.

These differences in peak warming stem from biodiversity conservation constraining large-scale negative emissions in the second half of the century. With reduced scope for BECCS and other land-intensive CDR options, mitigation pathways must achieve deeper emissions reductions earlier to remain within the same cumulative carbon budget. This front-loading of mitigation reduces the magnitude and duration of temperature overshoot.

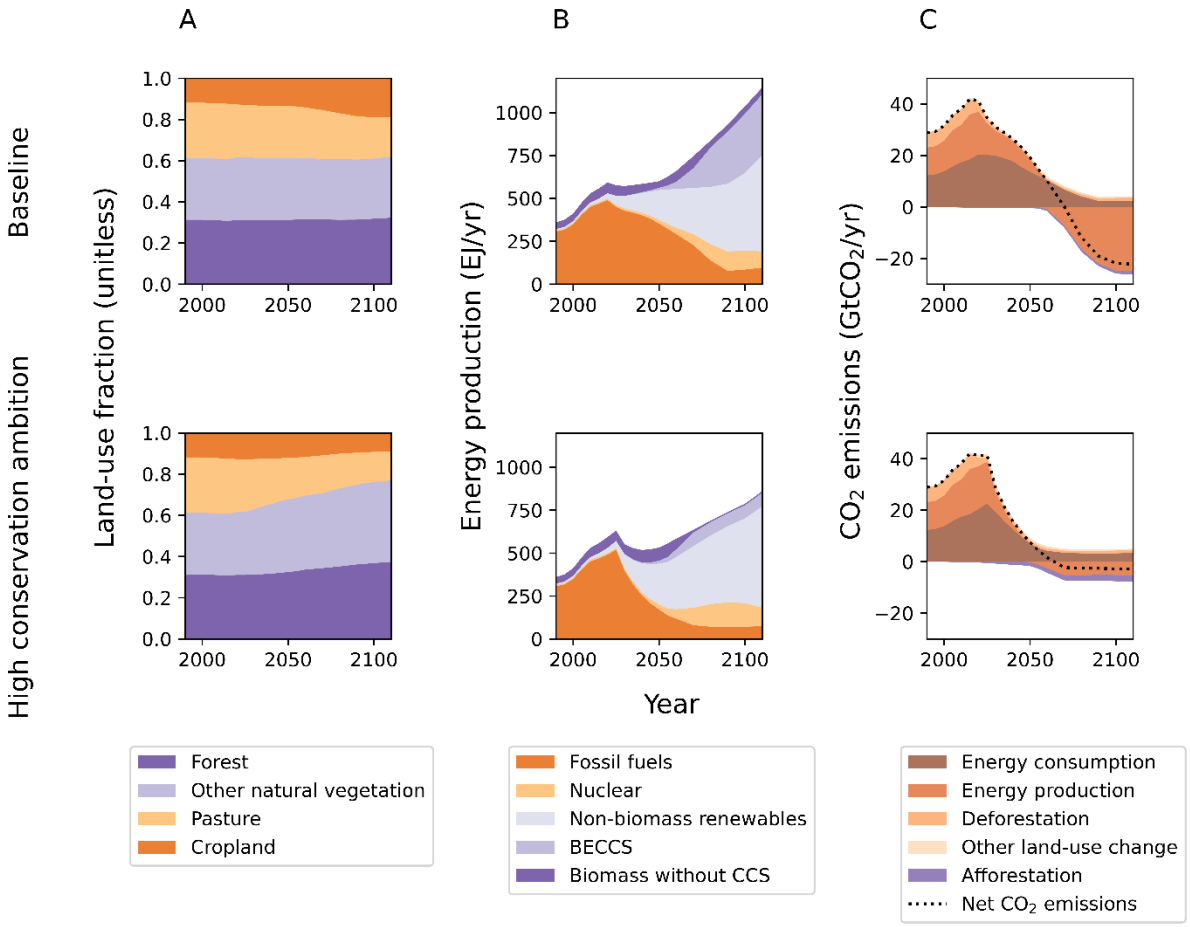

Figure 4. The impact of ambitious biodiversity conservation on global land-use, energy mix, and CO_2 emissions profiles for a 1,000 $GtCO_2$ full-century carbon budget. Top: baseline biodiversity conservation ambition, bottom: high biodiversity ambition. left to right: global land-use patterns, energy mix, and CO_2 emissions profile.

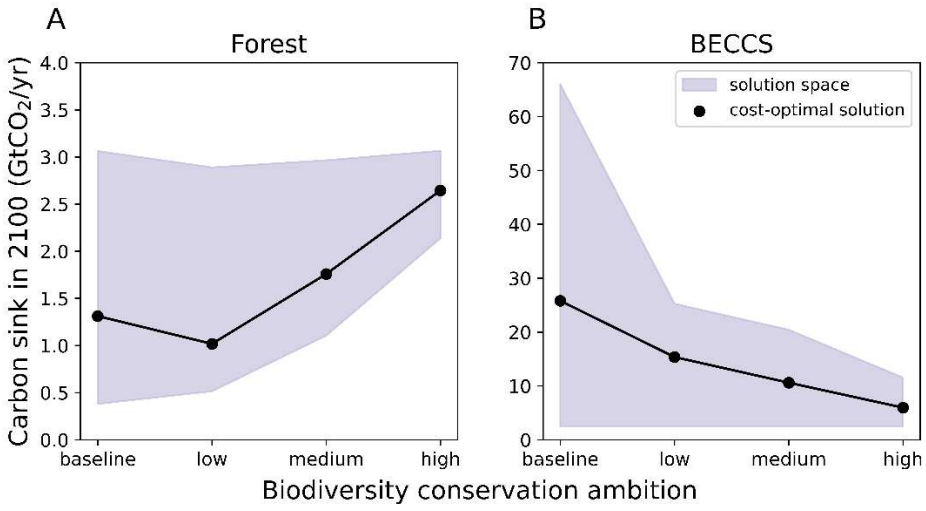

Figure 5. Effect of biodiversity conservation ambition on the CO_2 removal potential of land-based carbon sinks in the year 2100. Left: total forest CDR, right: BECCS CDR. The blue shaded region indicates the uncertainty space of allowed solutions. Black dots indicate the cost-optimal solutions found by MESSAGE*ix* for a 1,000 $GtCO_2$ full-century carbon budget. It is important to note that the amount of BECCS CDR under *baseline* biodiversity conservation ambition is an order of magnitude higher than the highest possible forest sink.

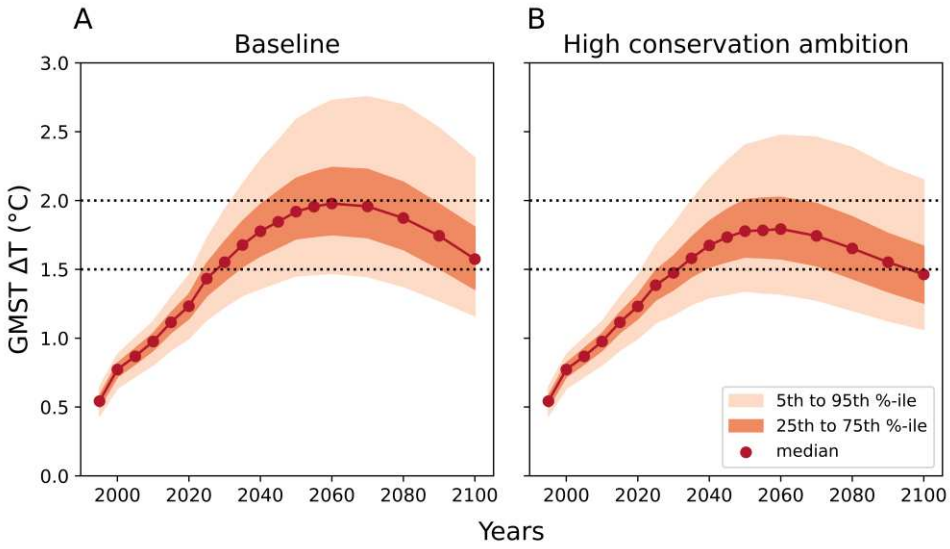

Figure 6. Effect of biodiversity conservation ambition on global warming under a full-century 1,000 $GtCO_2$ carbon budget, comparing the *baseline* ambition scenario (left) to *high ambition* (right). Δ*T* is the increase in global mean surface temperature (GMST) compared to pre-industrial levels.

This pattern is robust across carbon budgets (Figure 7A). Higher biodiversity conservation ambition systematically lowers peak warming for any given cumulative CO_2 budget. Conversely, cost-optimal solutions for scenarios without biodiversity constraints only achieve similarly low peak temperatures by adopting substantially tighter carbon budgets. Biodiversity conservation therefore reduces temperature overshoot by reshaping mitigation pathways within the same long-term carbon constraint.

Biodiversity conservation and the attainability of warming targets

We conduct a systematic analysis in which the stringency of the climate policy target is varied by exploring a range of full-century carbon budgets. Within this fully integrated energy-land system framework, the results show that biodiversity conservation plays a decisive role in determining which warming targets remain attainable.

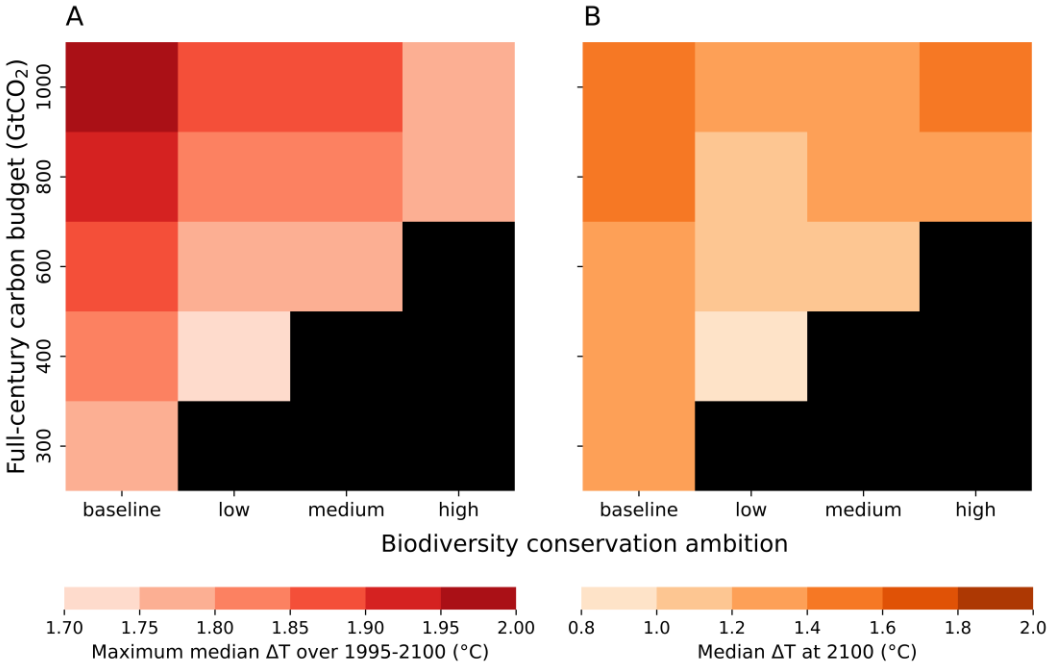

Figure 7. Effect of biodiversity conservation ambition and full-century carbon budget on Δ*T*. Heatmap of peak Δ*T* (left) and end-of-century (EOC) Δ*T* (right) for the four biodiversity conservation ambition levels and five full-century carbon budgets. Black cells represent infeasible scenarios, i.e., combinations of biodiversity ambition and carbon budget for which MESSAGE*ix* fails to find any solution.

While more ambitious biodiversity conservation policies support a reduction in temperature overshoot, they also render some of the lowest full-century carbon budgets unattainable (Figure 7B). This outcome reflects the strong dependence of very low warming targets on the availability of land- and biomass-based carbon dioxide removal options in the second half of the century.

As a consequence, long-term warming levels below approximately 1.2 °C by the end of the century cannot be achieved under highly ambitious biodiversity conservation policies. At the same time, keeping long-term temperature increase below 1.5 °C by 2100—consistent with the Paris Agreement—remains feasible across all biodiversity conservation settings considered. Even the highest biodiversity conservation ambitions are therefore compatible with achieving the Paris temperature goals, albeit constraining the attainability of the lowest possible warming targets that rely on extensive land- and biomass-based CDR.

Biodiversity conservation and the costs of mitigation

To explore the implications of biodiversity conservation for the costs of mitigation, we compute the average net present value (NPV) of the global carbon price from 2025–2100, discounted at 5 %, for these scenario combinations (Figure 8).

Naturally, mitigation costs increase with the stringency of the carbon budget. Further, for any carbon budget, increasing biodiversity conservation ambition systematically raises mitigation costs. This increase can be interpreted as the additional price society pays to meet both biodiversity and climate mitigation targets.

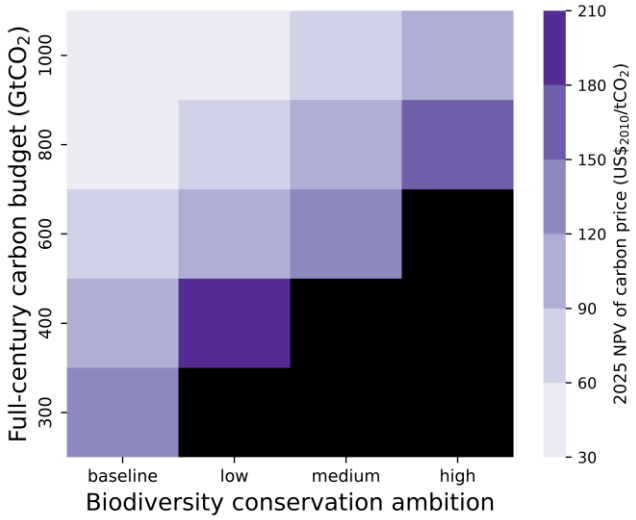

Figure 8. The effect of biodiversity conservation ambition and climate change mitigation ambition on the average NPV of the global carbon price between 2025 and 2100, discounted at 5 %. Black cells indicate infeasible combinations.

Discussion

In this study, we have made a systematic assessment of the interactions of biodiversity policies with land-based CDR methods. First, we assessed the effects of climate policy stringency and biodiversity conservation ambition separately. Our results suggest that climate mitigation policy in the land sector shows co-benefits for biodiversity but is not sufficient to counteract biodiversity loss in isolation, especially since it may shift biodiversity losses from carbon-rich biomes to others. Conversely, biodiversity conservation policies lead to some beneficial effects for climate mitigation, such as the protection and expansion of natural carbon sinks, while compromising on the availability and cost of BECCS.

We further explored the effects of joint implementation of climate and biodiversity policies. The limited availability of bioenergy, an important source of renewable energy as well as terrestrial CDR, incentivizes the energy supply system to phase out fossil fuels earlier and invest in solar and wind technology more rapidly. Emissions reduction has to take place sooner since the negative emissions potential in the latter half of the century is reduced. The importance of the forest-based carbon sink increases, while CDR through BECCS decreases. Increasing biodiversity conservation ambition also reduces the duration and extent of overshoot.

Our results agree with previous studies suggesting that cropland expansion for bioenergy production poses a threat to biodiversity (Rockström *et al* 2023, Hirata *et al* 2024, Núñez-Regueiro *et al* 2021, Van Vuuren *et al* 2010, Immerzeel *et al* 2014), with land-use change as the key driver of species loss. Further, we re-confirm co-benefits of climate mitigation for biodiversity conservation, especially through forest and other natural land protection and expansion (Harvey *et al* 2010,

Pörtner *et al* 2023). We build on this work with a systematic global assessment of bioenergy potentials under biodiversity conservation policies of varying ambitions and the effects of these policies and potentials on the land-energy nexus and climate system. This analysis utilizes a set of bioenergy and emissions price scenarios which span a large range, modelled in the newly implemented MAgPIE-MESSAGE*ix* integrated assessment framework. Utilizing this framework, we re-confirm a global limit for bioenergy production of around 100 EJ/yr in 2100 (Creutzig *et al* 2015) under ambitious biodiversity policies, which is lower than other previous estimates (Van Vuuren *et al* 2010). We further highlight co-benefits and trade-offs between biodiversity conservation and climate mitigation, such as the doubling of the forest carbon sink, and the palliative effect of biodiversity conservation on temperature overshoot driven by the more rapid and aggressive decarbonization needed to support these policies.

A limitation of this study is that we do not consider CDR beyond BECCS and re/afforestation. A more diverse portfolio would probably have a lower land footprint enabling even more ambitious combinations of biodiversity conservation and climate mitigation. Most notably, DACCS, if configured to be cost-effective, could become a significant land-sparing technology in the challenge of meeting ambitious climate targets.

Our results are conditional on the use of BII as a globally consistent biodiversity indicator. Various indicators for ecosystem health exist (Burgess *et al* 2024), and each of these captures some different aspects of it. BII is a relative metric that compares the species abundance of a given spatial location to the counterfactual situation without any human impact. As an indicator, BII is relatively straightforward for human understanding as well as numerical computation. However, BII would not respond to situations where the species composition (but not the abundance) were to change.

Further, the BII constraint in MAgPIE assigns the highest biodiversity values to forests. This allows replacement of open ecosystems such as savannas, grasslands, and shrublands with forests without incurring a biodiversity penalty. We thus conducted a cell-level co-occurrence analysis for the main biomass scenarios. The results indicate that about 20–99 Mha of forest expansion by 2100 coincide spatially with losses of natural land (supplementary information section S.2). This suggests that a non-trivial fraction of the modelled biodiversity gains from forest expansion may not materialize in practice, particularly in biodiversity-rich tropical grasslands such as the Brazilian Cerrado.

Differentiating BII scores by ecosystem type—rather than assigning a uniform maximum to all natural land—would strengthen future biodiversity assessments. Further, area-based metrics such as the Area of Habitat could be used to complement the BII measurement.

Finally, as our study does not consider the impacts of climate change on biodiversity directly, future work can expand this analysis by taking the related co-benefits of high climate policy stringencies into account.

Conclusion

Coordinated action on climate change mitigation and biodiversity conservation is essential for environmental sustainability. Our analysis demonstrates that it remains possible to achieve climate and biodiversity goals, but only if these objectives are pursued in an integrated manner that explicitly accounts for synergies and trade-offs across the energy and land-use sectors.

Using a new, fully integrated energy-land system framework, we show that ambitious biodiversity conservation reshapes pathways consistent with the Paris temperature goals. Biodiversity conservation reduces the availability of land-intensive mitigation options, particularly bioenergy (<100 EJ/yr) and BECCS (<6 $GtCO_2$/yr), and thereby limits the system's reliance on large-scale negative emissions in the second half of the century. As a consequence, mitigation pathways compatible with biodiversity conservation require steeper near-term emissions reductions and place greater emphasis on structural transformations of the energy system.

Accelerated fossil fuel phase-out and the rapid expansion of non-biomass renewable energy sources are critical for this. Scaling up wind, solar, and other low land-footprint climate mitigation technologies emerges as a key strategy for achieving deep decarbonization while minimizing pressure on ecosystems. These pathways allow climate targets to be met with substantially reduced dependence on land-based carbon dioxide removal, thereby alleviating conflicts with biodiversity conservation.

Importantly, we find that despite the more limited role of bioenergy and BECCS compared to many scenarios assessed in the IPCC AR6, global warming can still be brought back to 1.5 °C by the end of the century. However, our results also highlight that temperature overshoot must be carefully managed. Under ambitious biodiversity conservation, the reduced potential for negative emissions narrows the margin for correcting earlier emissions, making early and sustained mitigation essential to preserve the feasibility of returning to 1.5 °C within this century.

Overall, our findings underscore that climate mitigation and biodiversity conservation are not necessarily competing objectives, but they impose joint constraints on feasible transformation pathways. Successfully navigating these constraints requires prioritizing rapid emissions reductions, low land-intensity energy transitions, and coordinated policy frameworks that address climate and biodiversity goals together rather than in isolation.

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Data availability

The model data supporting the findings of this study are publicly available on Zenodo: 10.5281/zenodo.22124262.

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Biodiversity conservation policies alter the solution space of climate mitigation scenarios – Supplementary Information

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SI.1 Model Setup

We utilize a newly implemented integrated assessment framework based around the Model of Agricultural Production and its Impact on the Environment (MAgPIE[1]), and the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE*ix*[2]). The two models are linked via a land scenario look-up table used as input in the land-use emulator implemented in MESSAGE*ix*, similar to the GLOBIOM Land-Use Emulator[3]. For our production runs, we used MAgPIE version 4.6.7dev and MESSAGE*ix* version v3.9.0-71-gc25e7fc.

MAgPIE process

To create such a scenario look-up table, MAgPIE is used to solve a set of scenarios, varying in carbon and bioenergy prices. This process comprises three steps which can be recreated using the respective MAgPIE start scripts:

1. **Calculate baseline τ trajectory.** By default, MAgPIE has the option to endogenously invest in technological change (TC) which increases the land-use intensity indicator τ and thus productivity, costs, and environmental impacts, such as nitrogen leeching, of any affected crop and pasture area. When investigating bioenergy potentials at specific prices, this feature creates a positive feedback loop between the bioenergy prices, technological change investments, and resulting yield increases. To avoid this, bioenergy potentials are calculated using a pre-calculated, exogenous τ trajectory, extracted in this first step from a conservative scenario, assuming high costs for technological investments while satisfying the bioenergy demand curve defining the current MAgPIE default. Furthermore, biodiversity protection policies are implemented in this scenario, leading to a higher τ than a scenario without such policies, to avoid τ-induced infeasibilities in the most ambitious biodiversity scenarios investigated in this work. While the following steps 2 and 3 are necessary for each biodiversity conservation scenario and respective scenario matrix, this first step is executed only once, and the resulting τ trajectory is used across all related matrices.
2. **Model bioenergy potentials.** For each biodiversity conservation scenario, the price-driven bioenergy production potentials are modeled using the exogenous τ. To achieve this, we have expanded the MAgPIE model to be able to take energy-content based price signals for 1st and 2nd generation bioenergy in addition to bioenergy demand curves. Target prices are implemented linearly between 2020 (0 US$2005/GJ) and 2100 (0–45 US$2005/GJ). Additionally, we used modified demand curves that follow default demand until 2020, then phase baseline bioenergy demand out by 2050. As such, for price signals below production cost, no bioenergy is produced after 2050. Furthermore, potentials are calculated without a carbon price to assess the maximum potential without the interference of disincentivizing

[1] https://github.com/magpiemodel/magpie
[2] https://github.com/iiasa/message_ix
[3] https://docs.messageix.org/projects/global/en/latest/land_use/emulator.html

land-use change. The newly added price-driven feature is available in stable MAgPIE releases starting from version 4.8.0.

3. **Model emission profiles.** In step 3, we fix the regional bioenergy potentials extracted in step 2 as demand trajectories and vary carbon prices. Fixing the potentials this way ensures that the implementation of carbon prices only affects how and where this demand is met while keeping the gross production consistent between carbon price categories. This is a necessary condition to reduce inconvexities between scenarios in the final input matrix and resulting issues in MESSAGE*ix* scenarios using it. The bioenergy price signal is deactivated to ensure consistency. For each bioenergy production trajectory, we model carbon price scenarios of various stringency. These carbon prices are implemented based on the present value targeted for 2100 (0–4000 US$2005 / t CO_2) and a 5 % annual discounting rate. This translates to a 2025 starting value of roughly 2.6 % of the target value (0–103 US$2005/ t$CO_2$). In further contrast to the previous step, τ is calculated endogenously again since a bioenergy demand without additional price incentive avoids the positive feedback loop. At the same time, this enables MAgPIE to utilize technological change investments as one form of climate mitigation and biodiversity protection.

The MAgPIE start scripts for each step (see Table SI.1-1) are available through the public MAgPIE repository since version 4.8.0.

Table SI.1-1. Production steps and associated MAgPIE start scripts

Step	Script
Step 1	GENIE_1_tau-export
Step 2	GENIE_2_bm-priced
Step 3	GENIE_3_bm-demand

A shared configuration for all three steps is available in MAgPIE as scenario configuration preset 'GENIE_SCP'. This preset is loaded after the MAgPIE default configuration but before any step specific settings are set as described above.

To enable the use of the created data in MESSAGE*ix*, MAgPIE is run in a regional equivalent to MESSAGE*ix*'s R12 setup. To do so, MAgPIE's input data is prepared accordingly using the R package MADRaT. The data set versions used in this work are rev4.87 for regional, cellular, and validation data and rev4.43 for the additional data input. The project specific hash for the MESSAGE*ix* R12 regional setup is 26df900e.

Following the read-out of the raw matrix scenario indicators, they are combined into a single file and mapped onto MESSAGE*ix* compatible variables in the IAMC time-series format.

Land-use emulator

MESSAGE*ix* is used to find optimal scenario solutions for the coupled land-energy system under a combination of BII and carbon budget constraints. The model does not feature inherent biodiversity conservation constraints. As such, these constraints are implemented indirectly through the choice of MAgPIE matrix and its underlying scenario settings.

Data corrections during read-in

The selected MAgPIE matrix is read into MESSAGE*ix* using a pre-existing process used for other look-up tables, such as ones produced through GLOBIOM. As part of this process, a base price for each scenario region and time step is calculated based on the available bioenergy, the bioenergy price, the carbon savings compared to the next-lower carbon price category, and the current carbon price.

$$ScenPrice_{s_{b,e},t,r} = ScenPriceB_{s_{b,e},t,r} + ScenPriceE_{s_{b,e},t,r}$$

$$ScenPriceB_{s_{b,e},t,r} = Biomass_{s_{b,e},t,r} \times BiomassPrice_{s_{b,e},t}$$

$$ScenPriceE_{s_{b,e},t,r} = \max\left(0, \left(Emissions_{s_{b,e-1},t,r} - Emissions_{s_{b,e},t,r}\right) \times EmissionsPrice_{s_{b,e},t}\right) + ScenPriceE_{s_{b,e-1},t,r}$$

Where s is the scenario comprising biomass b and emission price e, t is the time step, and r is the region.

Due to path dependencies, a higher carbon price can be associated with higher emissions for late-century optimization time steps in MAgPIE, which would create a negative price term in the *ScenPriceE* calculation and possibly create issues in the following optimization. To avoid this, the maximum among 0 and the additional price calculation is used, setting *ScenPriceE* to the same price as the previous emission price category in case of the additional price calculation being negative.

Accounting for scenario history during optimization

MESSAGE*ix* blends the different land-use scenarios over time to create a new, virtual scenario. While there are constraints in place to avoid rapid switching between scenarios[4] issues can still occur, for example regarding emissions from land-use change. These are one-time emissions, occurring at the time of the conversion of, e.g., forest area to cropland. In some MAgPIE scenarios, especially those featuring relatively high biomass production, most of these changes may occur very early, reducing land-use emissions to a minimum in the second half of the century. In MESSAGE*ix* this may lead to a scenarios blend that mostly ignores these early emissions but profits from the high biomass production later on. In such a case, the scenario shows benefits of massive land-use change without the associated emissions, leading to an underestimation of land-use emissions and limiting the ability of the emulator to mirror MAgPIE's behavior.

To reduce this issue, we have expanded MESSAGE*ix*'s land equations to take the emissions and cost of the virtual scenario up to each optimization step into account. This way, emissions and cost of the virtual scenario account for the emissions and costs necessary to get to this point, not just the ones associated with the current time step itself.

For land-system greenhouse gas emissions $Emis$, the fundamental constraints are:

$$Emis_{t,r} = \sum_{s} Emissions_{s,t,r} \times Weight_{s,t,r} + \sum_{\dot{t}} EmisDebt_{t,\dot{t},r}$$

$$EmisDebt_{t,\dot{t},r} \geq \sum_{s} \left(Weight_{s,t,r} - Weight_{s,\dot{t},r}\right) \times Emissions_{s,\dot{t},r} - \sum_{\check{t}} EmisDebt_{\check{t},\dot{t},r}$$

Where s is the scenario (defined by biomass and emission price, as described above), and r is the region. t is the current time step, $\dot{t}, \check{t}$ are previous time steps, with, where both exist, $\dot{t} < \check{t} < t$. $EmisDebt$ is the embedded emissions in the current scenario mix that were not accounted for in previous optimization time steps and scenario mixes. $EmisDebt_{\check{t},\dot{t},r}$ needs to be taken into account when calculating $EmisDebt_{t,\dot{t},r}$ to avoid double counting of debt already accounted for.

The updated equations for the scenario costs *Cost* apply the same debt logic as the emissions equations above but additionally correct for the time step-specific discounting applied as part of MESSAGE*ix*'s cost optimization:

$$ScenCost_{t,r} = \sum_{s} ScenPrice_{s,t,r} \times Weight_{s,t,r} + \sum_{\dot{t}} CostDebt_{t,\dot{t},r}$$

$$CostDebt_{t,\dot{t},r} \geq \sum_{s} \left(\left(Weight_{s,t,r} - Weight_{s,\dot{t},r}\right) \times ScenPrice_{s,\dot{t},r}\right) \times \frac{df_{\dot{t}}}{df_t} - \sum_{\check{t}} CostDebt_{\check{t},\dot{t},r}$$

Where df_t is the discounting factor specific to time step t.

For both the emissions and the scenario cost equations, it holds that:

$$0 \geq Weight_{r,y,s} \leq 1$$

$$\sum_{s} Weight_{r,y,s} = 1$$

Feedback

To assess how well the MAgPIE emulator in MESSAGE*ix* represents MAgPIE and the land-use indicators it provides, MESSAGE*ix*'s blended scenarios are compared to the outputs of corresponding MAgPIE scenarios. For this purpose, three variables are exported from MESSAGE*ix* results and provided to MAgPIE as inputs: 2nd generation bioenergy crop demand, carbon price, and τ.

While a simple look-up table of course cannot perfectly reproduce the complexity of a partial-equilibrium model, results for example scenarios, shown in Figure SI.1-1, highlight the close relationship between the two. For both forest cover and cropland, we see that the MAgPIE feedback output is consistently within 5–10 % agreement with the MESSAGE*ix* solution.

[4] https://docs.messageix.org/en/latest/model/MESSAGE/model_core.html#land-use-model-emulator-section

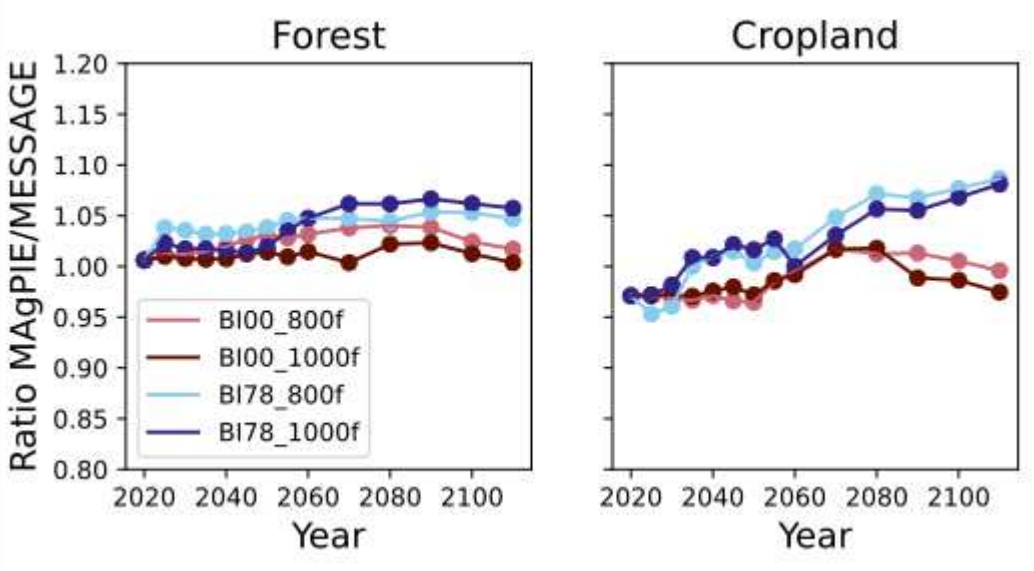

Figure SI.1-1. Ratio of the land cover types endogenously determined by MAgPIE feedback runs to the MESSAGEix cost optimal blended scenarios for forest (left) and cropland (right). The different colors show the four combinations of biodiversity conservation ambition (BI00: "baseline ambition", BI78: "high ambition") and net full-century CO_2 budget (800 and 1000 $GtCO_2$ net cumulative emissions in the optimization period 2025–2100).

As a general trend, MESSAGE*ix* overestimates CO_2 emissions from the land sector for a given biomass amount and AFOLU carbon price, especially in the second half of the century (Figure SI.1-2). As a main variable to be minimized during optimization under a carbon price, this is to be expected as MAgPIE as a model has more freedom to respond to a specific set of demands and price signals compared to the emulator's relatively rigid scenario table. Further, since the emulator consistently overestimates the emissions, they can be considered a conservative estimation of AFOLU emissions and can be systematically corrected.

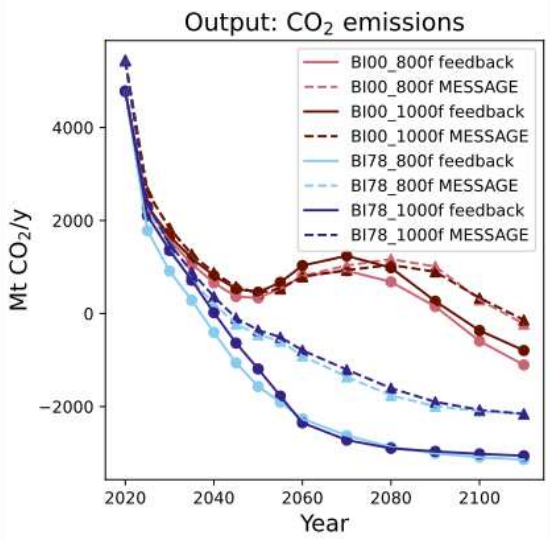

Figure SI.1-2. Comparing the AFOLU CO2 emissions output of the MAgPIE feedback run (solid) with the MESSAGE*ix* solutions (dashed). The different colors show the four combinations of biodiversity conservation ambition (BI00: "baseline ambition", BI78: "high ambition") and full-century CO2 budget (800 and 1000 GtCO2 net cumulative emissions in the optimization period 2025–2100).

SI.2: Cell-level displacement of natural and extensive land by planted forests

We conduct a spatial analysis of the MAgPIE land-use changes to assess areas where the uniform *BII = 1* scoring for mature forest might not capture genuine ecological improvements sufficiently—specifically, where planted forest expansion displaces open ecosystems and/or extensive grazing lands whose real-world biodiversity value in the model is not distinguish from forests. For doing so, we quantify the spatial co-occurrence of planted forest expansion and natural land loss using three complementary methods applied to the MAgPIE 0.5° gridded land-use output (59,199 cells, 1995–2110). All three

methods compare cell-level changes relative to a 2025 baseline and use the same displacement metric: for each cell where planted or anthropogenic forest increased and natural land decreased simultaneously, *displacement = min(forest gain, natural loss)*. This conservative metric ensures that displacement cannot exceed either the gain or the loss in any cell. Cells where only one changes (gain without loss, or loss without gain) score zero.

Method 1: Planted forest displacing natural land

Natural land is defined as the sum of primary forest (primforest), secondary forest (secdforest), and other natural vegetation (other). Planted forest comprises three MAgPIE categories: PlantedForest_Timber, PlantedForest_Afforestation, and PlantedForest_NPiNDC. For each cell and time step, we compute the change in planted forest and the change in natural land relative to 2025. Where planted forest increased and natural land decreased in the same cell, displacement is the minimum of the two absolute changes. This method is entirely internal to MAgPIE and requires no external datasets.

Table SI.2-1. Method 1: Planted forest displacing natural land by 2100.

Scenario	Δ Planted (Mha)	Δ Natural (Mha)	Δ Primforest	Δ Other	Displacement (Mha)
Technical Potential	+2	−1,631	−348	−768	20
Stop Biodiversity Loss	+47	−407	−43	−186	26
Minimal Production	+266	+1,547	−114	+1,933	31
Sustainable Potential	+147	+1,624	−129	+2,045	21

Natural = primforest + secdforest + other. Displacement = cell-level min(planted gain, natural loss). All changes relative to 2025.

Method 2: Anthropogenic forest displacing primary natural land

Secondary forest in MAgPIE represents regrowth on previously cleared land and is anthropogenic in origin. Method 2 reclassifies secondary forest from the natural to the anthropogenic category. Natural land is thus defined as primary forest plus other natural vegetation, while anthropogenic forest comprises secondary forest plus all three planted forest types. The displacement metric is otherwise identical to Method 1. This reclassification matters most in scenarios with large secondary forest dynamics (e.g., Technical Potential: displacement rises from 20 to 99 Mha by 2100).

Table SI.2-2. Method 2: Anthropogenic forest displacing primary natural land by 2100

Scenario	Δ Anthro (Mha)	Δ Natural (Mha)	Δ Primforest	Δ Other	Displacement (Mha)
Technical Potential	−513	−1,116	−348	−768	99
Stop Biodiversity Loss	−132	−229	−43	−186	63
Minimal Production	−7	+1,819	−114	+1,933	46
Sustainable Potential	−145	+1,916	−129	+2,045	47

Natural = primforest + other. Anthropogenic = secdforest + planted. Displacement = cell-level min(anthro gain, natural loss). All changes relative to 2025.

Method 3: Planted forest displacing natural land and extensive pastures

MAgPIE pasture (past) encompasses both intensive livestock production and extensive grazing on savannas, grasslands, and shrublands. Method 3 uses the Keith et al. (2022) open ecosystem (OE) map[5] to distinguish between these two uses. For each cell, extensive pasture is defined as:

$$extensive\_pasture(cell) = \min(past(cell), \max(0, OE(cell) - other(cell))$$

[5] Keith, D.A., Ferrer-Paris, J.R., Nicholson, E. et al. A function-based typology for Earth's ecosystems. Nature 610, 513–518 (2022). https://doi.org/10.1038/s41586-022-05318-4

where OE is the Keith et al. open ecosystem area (biomes T3–T6, gridded to 0.5°) and other is MAgPIE's own 'other natural vegetation' category.

The rationale is that the Keith OE map identifies the total extent of open ecosystems in each cell. MAgPIE already captures part of this as 'other'. The residual OE area that MAgPIE does not classify as 'other' likely corresponds to extensive grazing on what is ecologically an open ecosystem. The extensive fraction is capped at the actual pasture area to avoid overcounting.

At the 2025 baseline, this procedure classifies 2,311 Mha as extensive pasture (72% of total MAgPIE pasture of 3,220 Mha) and 909 Mha as intensive. The extensive fraction per cell is frozen at its 2025 value and applied to future pasture areas, so that the classification reflects baseline land character rather than evolving with the scenario. Natural land for Method 3 is then defined as 'other' plus extensive pasture, and displacement is computed against planted forest gains using the same cell-level co-occurrence metric as Methods 1 and 2.

Table SI.2-3 Method 3: Planted forest displacing natural land and extensive pastures by 2100

Scenario	Δ Planted (Mha)	Δ Nat+ExtPast (Mha)	Δ Other	Δ Ext. Pasture	Displacement (Mha)
Technical Potential	+2	−1,157	−768	−389	26
Stop Biodiversity Loss	+47	−388	−186	−202	32
Minimal Production	+266	+754	+1,933	−1,179	65
Sustainable Potential	+147	+796	+2,045	−1,249	42

Natural = other + extensive pasture (Keith OE-informed, 72% of total pasture at 2025 baseline). Displacement = cell-level min(planted gain, natural+ext.pasture loss). All changes relative to 2025.

Summary of displacement estimates

Across the three methods, cell-level displacement of natural and extensive land by planted or anthropogenic forest ranges from 20–99 Mha by 2100, depending on the scenario and the definition of natural land (Tables S1–S3). Technical Potential produces the largest Method 2 displacement (99 Mha) because secondary forest dynamics drive the co-occurrence signal, despite minimal planted forest expansion (+2 Mha). Minimal Production produces the largest Method 3 displacement (65 Mha) because of its substantial planted forest expansion (+266 Mha) targets cells where extensive pasture is declining (−1,179 Mha).

The BII78 scenarios (Minimal Production, Sustainable Potential) show a distinctive pattern: 'other' natural vegetation expands massively (+1,933 to +2,045 Mha) under the biodiversity constraint, but extensive pasture still contracts (−1,179 to −1,249 Mha) and primary forest declines in all scenarios (−43 to −348 Mha). Displacement in BII78 scenarios (21–65 Mha depending on method) reflects the fact that planted forest expansion is spatially targeted at cells where extensive land use is declining.

Reclassifying secondary forest as anthropogenic (Method 2) has the largest effect on Technical Potential (20 → 99 Mha) and Stop Biodiversity Loss (26 → 63 Mha), where secondary forest dynamics drive the displacement. Including extensive pasture (Method 3) has the largest effect on Minimal Production (31 → 65 Mha) and Sustainable Potential (21 → 42 Mha), where planted forest expansion into former grazing lands is the primary displacement channel.

In extreme scenarios, such as the High Climate Ambition Scenario without explicit BII constraints, the displacement may reach 300 Mha.