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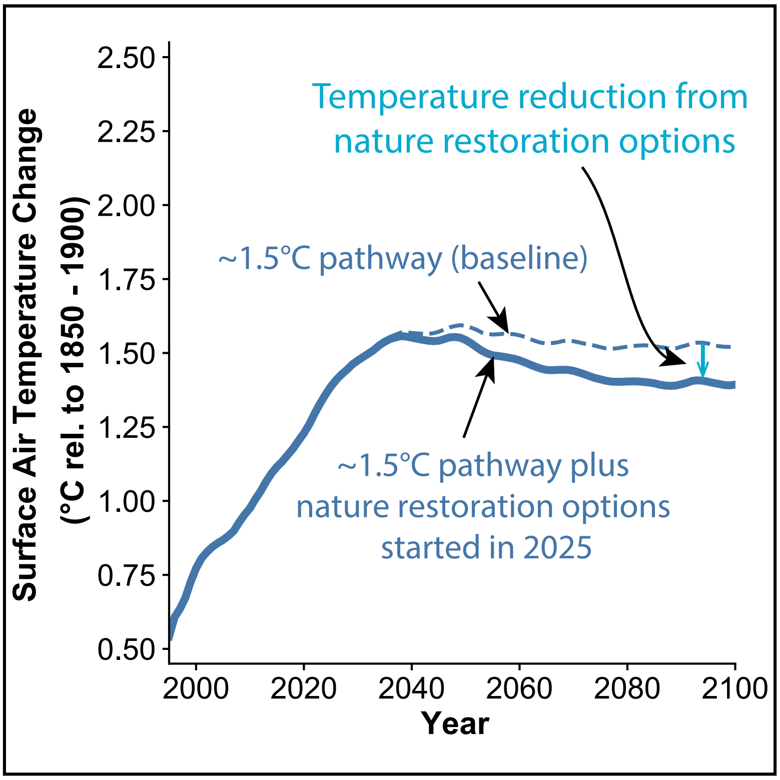
Graphical abstract



Highlights

- A “responsible development” approach to nature restoration minimizes land-use change
- We assess the responsible potential for land removals at 103 GtC over the century
- Land removals cannot be scaled up quickly enough to noticeably reduce peak global temperatures
- Nature restoration is crucial but cannot offset fossil fuel emissions for net zero

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In brief

Nature restoration is critical for responding to multiple global crises, including biodiversity loss and climate change. However, nature restoration cannot be scaled up quickly enough to noticeably reduce peak global temperatures and is ultimately limited by existing uses of land. While restoring ecosystems is crucial for planetary health, it is no substitute for preventing emissions from fossil fuels. Ongoing emissions cause extra warming compared with a world in which those emissions never happened—warming that cannot be compensated by nature restoration.

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Carbon removals from nature restoration are no substitute for steep emission reductions

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SCIENCE FOR SOCIETY Growing commitments to net-zero emissions by 2050 to achieve the Paris Agreement goals are a welcome step forward on climate action but have also seen an increasing focus on nature restoration to remove carbon dioxide from the atmosphere. This risks over-relying on land for mitigation at the expense of phasing out fossil fuels. At the same time, a wide range of activities are being labeled "nature restoration," some of which, such as monoculture tree plantations, degrade nature—destroying biodiversity, increasing pollution, and removing land from food production. We apply a "responsible development" framing to imagine a constrained approach to nature restoration, guided by ecological principles. Quantifying the resultant carbon uptake and temperature impacts shows that nature restoration can marginally lower peak warming, but any climate benefits are dwarfed by the scale of ongoing fossil fuel emissions. We conclude that more "zero" and less "net" is required for 2050 climate targets.

SUMMARY

The role of nature restoration in mitigating the impacts of climate change is receiving increasing attention, yet the mitigation potential is often assessed in terms of carbon removal rather than the ability to meet temperature goals, such as those outlined in the Paris Agreement. Here, we estimate the global removal potential from nature restoration constrained by a "responsible development" framework and the contribution this would make to a 1.5°C temperature limit. Our constrained restoration options result in a median of 103 GtC (5%–95% range of −91 to 196 GtC) in cumulative removals between 2020 and 2100. When combined with deep-decarbonization scenarios, our restoration scenario briefly exceeds 1.5°C before declining to between 1.25°C and 1.5°C by 2100 (median, 50% probability). We conclude that additional carbon sequestration via nature restoration is unlikely to be done quickly enough to notably reduce the global peak temperatures expected in the next few decades. Land restoration is an important option for tackling climate change but cannot compensate for delays in reducing fossil fuel emissions.

INTRODUCTION

The potential for atmospheric carbon-dioxide removal (CDR) is a growing area of research, and the Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5°C has confirmed that some level of CDR will be essential for limiting warming to 1.5°C, or even below 2°C, above pre-industrial levels.[1] Even the most ambitious decarbonization pathways rely on (lower) levels of CDR.[2] Yet CDR options that are reliant on significant land-use change, such as bioenergy with carbon capture and storage (BECCS) and afforestation or reforestation (AR), remain predominant in integrated assessment modeling and climate-policy debates.[3,4] Research so far has focused on techno-economic and acceptability framings of CDR feasibility without sufficient consideration of the environmental and social impacts of extensive land-use change. While broader concerns are beginning to be reflected in the scenario literature, with an increasing focus on delivering sustainable development in future climate mitigation scenarios,[5–7] AR is still often included uncritically without differentiating between removal options with strong co-benefits and those that could cause negative impacts to biodiversity, livelihoods, and food security.

The concept of a responsible development framing of CDR is one that not only considers the feasibility of CDR in terms of

Table 1. Land-use and management characteristics of land-management pathways

	Primary land use	Management intervention	Pathway
Improved ecosystem integrity	restoration	land-use change	forest restoration (from productive use to restoration, allowing secondary forests to reach their biological potential)
		land-cover change	reforestation (from deforested to forested land via natural regeneration)
	production	reduced production	reduced harvest (reduced logging intensity) and silvopasture (reduced grazing intensity)
		increased productivity	agroforestry (increased crop productivity) and silvopasture (alternative feed sources)

social and environmental sustainability constraints but also attends to the consequences that CDR pathways may have on meeting the temperature targets of the Paris Agreement.[8] Doing so requires examining contestations between alternative approaches to mitigation, which in turn can bring to the fore the value judgements and conflicts represented in alternative pathways to 1.5°C. The concern over heavy reliance on CDR in 1.5°C pathways relates in large part to the reliance of BECCS and AR on land-use change,[3,8] as well as to the potential for what has been referred to as "mitigation deterrence," whereby expectations for future removals delay or replace near-term emission reductions.[9]

While recent studies have sought to understand the upper bounds for removals via nature restoration,[10–12] here we assess what we call the "responsible" sequestration potential within social and environmental constraints that go beyond avoiding urban and agricultural areas to base restoration activities on ecological principles. We then demonstrate the potential contribution from nature restoration to limiting peak warming and reducing global temperatures over the century. Our study goes beyond existing literature that assesses the temperature impacts of nature restoration[13] by also interrogating the land-use removal options. We do this by differentiating between activities that restore degraded lands or forests and other AR, a distinction that is rarely made in the literature. On the basis of this distinction, we develop five land-management pathways to assess an ambitious potential for ecosystem restoration (beyond what countries have pledged) while assessing a constrained potential for reforestation (to the extent that countries have pledged). This distinction matters because reforestation requires a land-use change and therefore presents more risks and potential tradeoffs than restoring degraded lands while maintaining existing land uses. We suggest that this combination presents the maximum responsible land-restoration potential that is available to contribute to climate mitigation. On the basis of this removal potential, we assess the impacts on peak warming and century-long temperature reduction.

RESULTS

Ecosystem restoration pathways

Given that healthy ecosystems are critical for combating climate change,[14] we rely on principles of ecological restoration to guide land interventions that are inherently beneficial—to climate, biodiversity, and people—thereby building ecological resilience and human capacity.[15–17] A simplistic typology of these key characteristics is depicted in Table 1, which is used to guide the selection of five land-management pathways that represent different approaches to ecosystem restoration. These are represented by primary land-use objective (restoration or production), management intervention (land-use change, land-cover change, or change in production intensity), and impact on ecosystem integrity.

The carbon-sequestration potential of the five land-management pathways that aim to restore ecosystem integrity (which we refer to as ECORES) is quantified between 2020 and 2100 by an area-based approach and estimates of land carbon flux (details are provided in the experimental procedures). While peatland, coastal, and marine ecosystems are among the most carbon dense in the world, at a global scale, the potential for carbon sequestration in coastal and marine ecosystems is orders of magnitude lower than that in terrestrial ecosystems,[18] and peatland restoration results in (significant) avoided emissions rather than additional sequestration.[19] For these reasons, terrestrial carbon removals are the focus of this study, although the impact of avoided emissions on temperature is included in the baseline options. The pathway characteristics are summarized in Table 2 (details in Tables S2–S7). We then present a 1.5°C compatible scenario combining ecosystem restoration with deep decarbonization pathways (the RESTORE scenario). The ecosystem restoration pathways (ECORES) included here build on previous work in Teske et al.[20] and Littleton et al.[21] by using updated datasets and extending the analysis from these previous studies.

The results show the median gross cumulative potential of additional CDR with five ECORES to be 103 Gt carbon (GtC) (5%–95% range of −91 to 196 GtC) between 2020 and 2100. The peak annual sequestration rate from all ECORES (forest restoration, reforestation, reduced harvest, agroforestry, and silvopasture) is a median of 2.6 GtC per year (5%–95% range of 1–5 GtC per year), although this rate is only maintained for 1 to 2 decades (Figure 1). The average annual sequestration rate from 2020 to 2100 is 1.2 GtC per year. These removals will be canceled out to some extent by ongoing net land-use emissions, discussed in section "temperature pathways." These results are approximately 10% higher than the carbon removals found when the same land-management pathways were modeled in a dynamic global vegetation model (DGVM); the difference is largely due to the inclusion of soil carbon response to land-use change in the DGVM.[21] However, given the very different methodological approaches to quantifying carbon removal, the similarity increases confidence in the results.

Figure 1 shows that while the sequestration potential of restoration pathways scales up over time, pathways reliant on

Table 2. Five ecosystem restoration pathways (ECORES)

	Pathway	Description
Forested lands	forest restoration	set aside degraded natural (secondary) forests for conservation purposes; all biomes (1,893 Mha or 25% of secondary forests)
	reduced harvest	reduction of harvest intensity in temperate and boreal managed forests (221 Mha or 19%) and ceasing industrial harvest in tropical forests (532 Mha or the remaining 75%)
	reforestation	reforestation of mixed-native species in tropical and temperate biomes; maintained for conservation purposes (the 211 Mha pledged for reforestation under the Bonn Challenge as of 2021 included here)
Agricultural lands	agroforestry	integrating trees in existing croplands over 20% of temperate and tropical croplands (278 Mha)
	silvopasture	increased trees and shrubs over 10% of temperate and tropical pastureland (308 Mha) via reduced grazing intensity

removing disturbances see a jump in annual sequestration potential after a 20-year implementation period. During the 20-year implementation period, sequestration from regrowth is considered non-additional. We include the sequestration only after 20 years, when removal factors for old forests apply.[22] All five ECORES are implemented in temperate and tropical regions, while only two pathways (forest restoration and reduced harvest) are also implemented in the boreal region. The highest uncertainty levels are confined to the temperate region as a result of uncertainties in removal factors in temperate managed forests.[22,23] This is consistent with the understanding that the contribution from land-based carbon removals to climate change mitigation efforts remains highly uncertain,[24] given that the terrestrial component is the most uncertain of the global carbon budget, particularly regarding the magnitude of the land-carbon flux in northern latitudes.[25]

We find the highest rates of carbon removal from reforestation in the tropics. This is due to higher carbon-sequestration potential in full regrowth from deforested to forested land than in recovering carbon stocks in degraded forests,[22] although it is important to also consider the mitigation benefit of maintaining the carbon stocks in existing forests (see below). Our land area for the reforestation pathway is based on current Bonn Challenge pledges,[26] of which only around 5% are in temperate regions (and none in boreal), meaning that the majority of reforestation included here occurs in the tropics. However, unlike existing pledges, we assume that all areas will be reforested with a diversity of native species that are thereafter maintained as standing carbon stocks. Analysis shows this is not the case in reality given that around half of these pledges are for commercial plantations.[16] The difference between natural forest restoration and commercial timber plantations can be as much as a 90% reduction in long-term carbon sequestration and storage,[16] meaning that the carbon-sequestration potential of tropical reforestation would be significantly lower under current restoration pledges than under our idealized assumptions.

The forest restoration and reduced harvest pathways result in similar levels of carbon removal. This is due to similarities in the pathways that both represent removing or reducing disturbance in degraded natural forests, although at the global scale, reduced harvest occurs over a greater land area, resulting in higher removals for this pathway (Figure 1). The key difference between the two pathways is in the intensity of changed land management, such that forest restoration allows full recovery of carbon carrying capacity in one-quarter of secondary forests (removing these forests from production and increasing the proportion of conservation areas). Reduced harvest, on the other hand, represents a reduction in harvest intensity, which research suggests would allow an increase in forest carbon stocks over time while commercial harvest continues.[27–29] However, this benefit is only apparent in temperate and boreal regions, and there is evidence that tropical forest carbon continues to decline with any level of commercial harvest.[11,30–33] Hence, in the reduced harvest pathway presented here, there is no commercial harvest of tropical forests, meaning that they are allowed to restore to full carbon carrying capacity in a manner similar to the forest restoration pathway. The impact of carbon storage in harvested wood products (HWPs) is excluded here because of sensitivity analysis suggesting that long-term mitigation benefits may be overestimated.[34] Reducing forest harvest also provides an immediate mitigation benefit of reducing emissions from forest degradation, which we quantify for the land area in these pathways as 0.03 GtC per year according to an average value of 35% carbon density reduction through degradation.[35] These avoided emissions are represented in the land-use baseline (see experimental procedures).

The pathways representing restoration of agricultural areas—agroforestry and silvopasture—allow for existing land uses to continue. Agroforestry can be implemented in many different ways, but here it is assumed to be the integration of additional trees into agricultural landscapes, which results in significant sequestration across large areas of temperate and tropical croplands. Silvopasture—a complex and intensively managed system combining trees, forage plants, and livestock—has been shown to increase biodiversity and carbon storage, sometimes to levels commensurate with forested landscapes.[36,37]

The total carbon removal from all five ECORES—a median of 103 GtC cumulative sequestration by 2100 in addition to ongoing land-management activities—is shown in Figure 2. This represents the lower end to the middle of estimated ranges for land-based removals (approximately 30–217 GtC),[38] reflecting the conservativeness of our approach in avoiding double counting and minimizing land-use change. The regional differences shown in Figure 2 relate primarily to the climatic biome differences already discussed above. Higher rates of sequestration are seen in Asia, Latin America, and Africa, where tropical biomes see higher net primary productivity. Greater land area is also included in the tropics because the Bonn Challenge pledges are predominantly located in tropical forested countries. The difference in the reduced harvest pathway between temperate and tropical biomes, where commercial harvest of native forests was entirely halted in the tropics, is also a key contributor to higher sequestration rates in these regions.

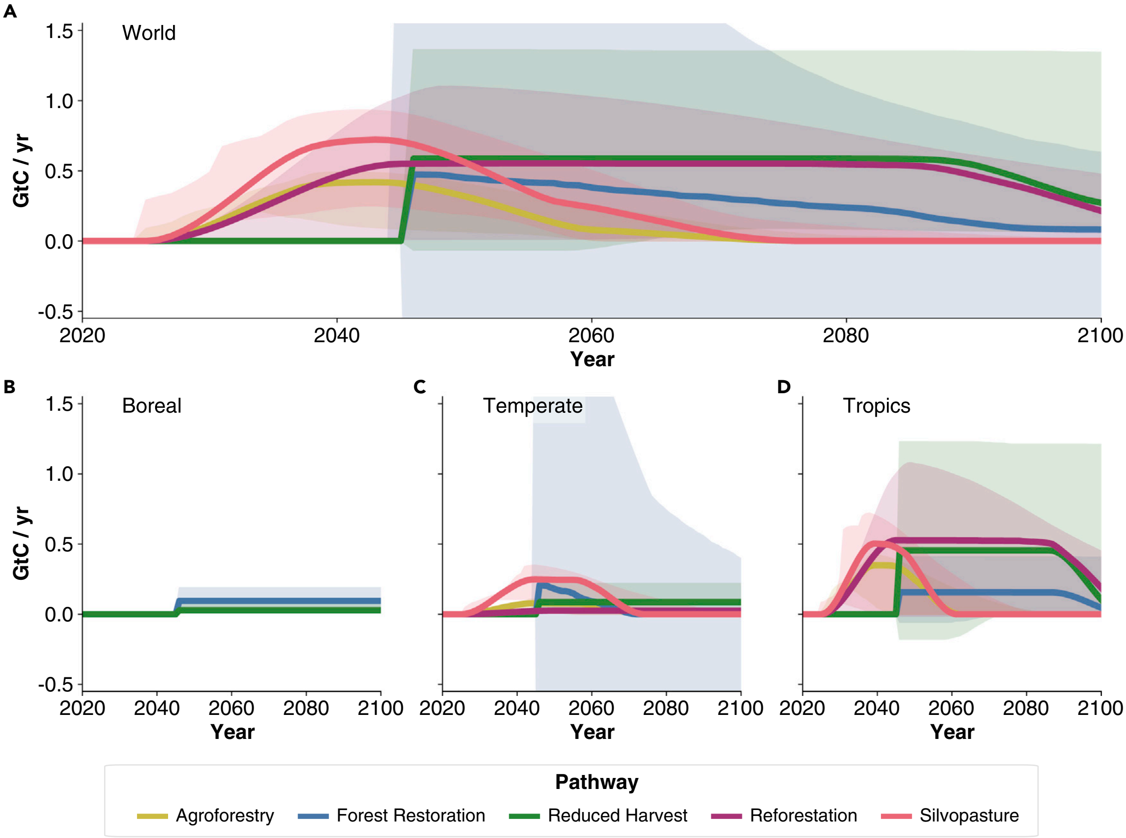

Figure 1. Annual removals over the century for the five ECORES

World total for each pathway (A) and totals for different climatic biomes (B–D). Solid lines represent the median, and shaded areas show the 5th–95th percentile range. The large range in temperate-zone forest restoration is primarily due to large uncertainties on emission-removal factors rather than the impact of land-management interventions.

Temperature pathways

For temperature projections, we use a reduced-complexity probabilistic climate emulator that reflects the updated climate science understanding in line with the IPCC Sixth Assessment Report (namely the AR6 calibrated version of MAGICC v7.5). We find that our scenarios are in line with limiting warming to 1.5°C by the end of the century, although we will at best have a roughly 50/50 chance of staying below this limit (Figure 3). While the ecosystem-restoration options provide a contribution, this ability to limit warming to around 1.5°C rests primarily on our assumed energy and industrial emission pathways, i.e., deep-decarbonization pathways that assume a swift transition to 100% renewable energy (University of Technology Sydney [UTS]),[39] strongly reduced energy demand (low energy demand [LED]),[2] or a scenario version that combines these two characteristics with behavioral changes (IMA15-TOT).[40]

Achieving this would require CO_2 emissions to peak within the next few years, if not already. We base this conclusion on the UTS scenario,[39] which follows recent emissions trends from the Global Carbon Project and additionally assumes that 2021 emissions will return to their 2019 peak after the COVID-19 blip. Some scenarios from the SR1.5 database[41] have earlier peak emissions dates because they have not been re-harmonized to follow recent emissions trends. The fact that the scenarios do not follow historical emissions exactly is a frequently encountered issue in the scenario literature. However, given that longer-term emission trends are not invalidated by a few years of historical emissions, the scenario community tends to apply harmonization routines, which we also employ here. More generally, though, past peak emission dates in previous scenarios emphasize the need for strong emission reductions to begin as quickly as possible in order to pursue emission trajectories without large additional mitigation costs, e.g., due to the near-term decommissioning of recently built fossil fuel infrastructure.

In the combined scenario presented in Figure 3, we use our default land-use baseline (shared socio-economic pathway 1 [SSP1]-baseline minus reported carbon sequestration) with positive net land-use emissions over the century that decline to <1 GtC per year by 2050 and <0.5 GtC per year by 2100. These ongoing land-management activities represent 65 GtC in cumulative emissions over the remainder of the century. These net land-use emissions are offset by additional removals via our five ECORES (Figure 3) to result in 32 GtC net removal over the century. The temperature pathway when combining the full potential of land-use removals achieved via ecosystem restoration with emissions from three different low-energy scenarios and the default land-use baseline is shown in Figure 3. These results

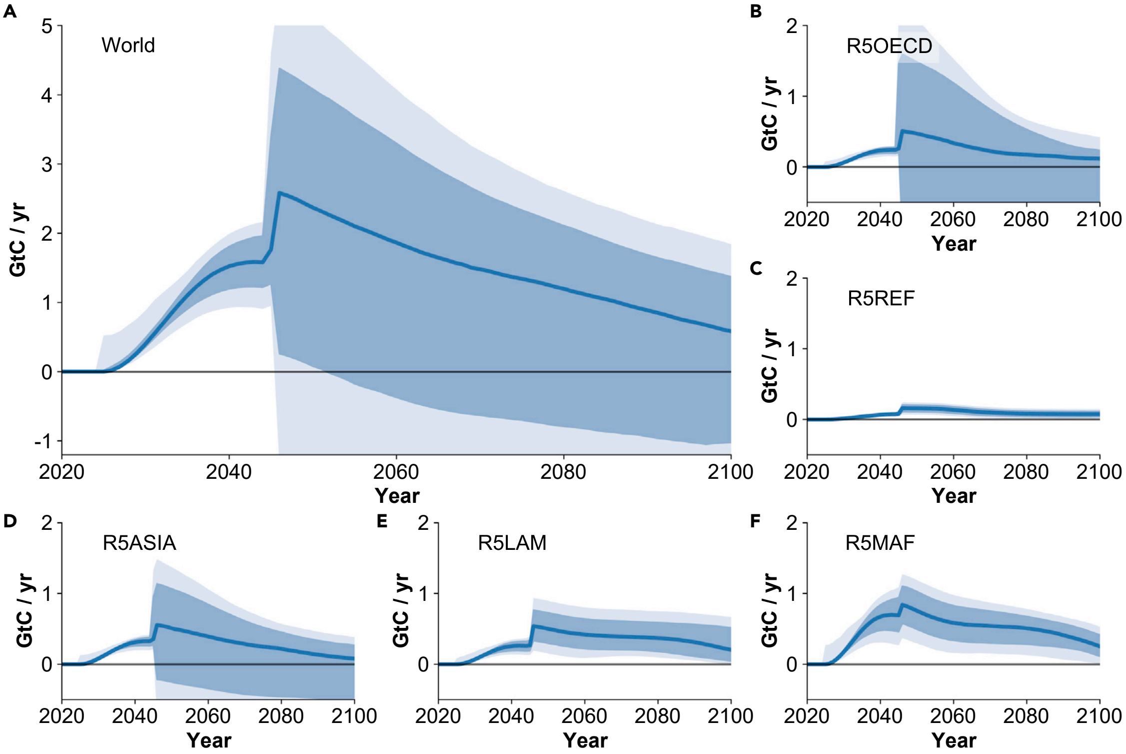

Figure 2. Total additional carbon removals to 2100

(A) Global total.

(B–F) Totals based on the Organisation for Economic Cooperation and Development (OECD) five world regions: (B) OECD 90 + EU (R5OECD), (C) reforming economies (R5REF), (D) Asia (R5ASIA), (E) Latin America (R5LAM), and (F) the Middle East and Africa (R5MAF).

Solid lines represent the median, and shaded areas show the 5th–95th percentile range.

show that the scale of CDR achieved via ecosystem restoration is sufficient to be compatible with the 1.5°C pathway but only when coupled with the most ambitious deep-decarbonization scenarios.

Removals via land sequestration have an almost undetectable impact on the change in 2031–2050 (approximately peak) temperatures (Figure 3B), as the 2031–2050 mean temperature is determined much more strongly by the fossil and energy-transformation pathway. This means that additional carbon sequestration via land management will not significantly improve the chances of limiting peak warming to 1.5°C; the underlying cause is the time delay, or "phase-in period," of around 20 years between land-management interventions and carbon removals. For reforestation, agroforestry, and silvopasture, this lag time is to allow new forests, trees, and shrubs to grow. For pathways that allow restoration of degraded forests, there is a similar phase-in period to allow non-additional regrowth that would normally occur after timber harvest. Given that peak warming is now expected to occur within the next 10–20 years in the strong mitigation scenarios and it takes time to scale up land-based removals, these interventions do not strongly affect the peak temperature, but they do contribute to a temperature decline, on the order of 0.1°C (median), by the end of the century. The different temperature impacts between peak and end-of-century warming are also reflected in the difference between our 95% (higher uptake, lower temperature) and 5% (lower uptake, higher temperature) estimates. The difference between the 5% and 95% is less than 0.05°C for peak temperatures, reflecting limited effects of removals by 2050. For 2100 warming, the uncertainty is much larger. At the upper end (95%), warming could be 0.25°C lower in 2100 than with our no-removal baseline.

We next explore the impact of phasing out ongoing land-use emissions, which in the ECORES default land-use baseline declines but remains positive until the end of the century. Bringing land-use baseline emissions to net zero (assuming land-use activities balance positive and negative emissions) through changing the default land-use baseline to halt deforestation (by 2050, 2040, or 2030) increases the additional carbon-removal potential to 64, 76, or 87 GtC, respectively (Figure 4). However, halting deforestation by 2030 (baseline 2030) compared with ongoing land-use and land-use-change emissions over the century (default) has a very small impact on peak temperature (Figure 4B) but reduces warming over the century by approximately 0.08°C (Figure 4C).

While the timing of reductions in deforestation does not have a significant effect on global mean temperatures, this should not be taken to mean that ongoing deforestation and forest degradation are acceptable for multiple reasons. First, ongoing deforestation will increase temperatures, even if at a relatively slower rate than the warming caused by ongoing use of fossil fuels. Second, our scenarios cover only the case where deforestation is approximately constant or decreases. A significant increase in

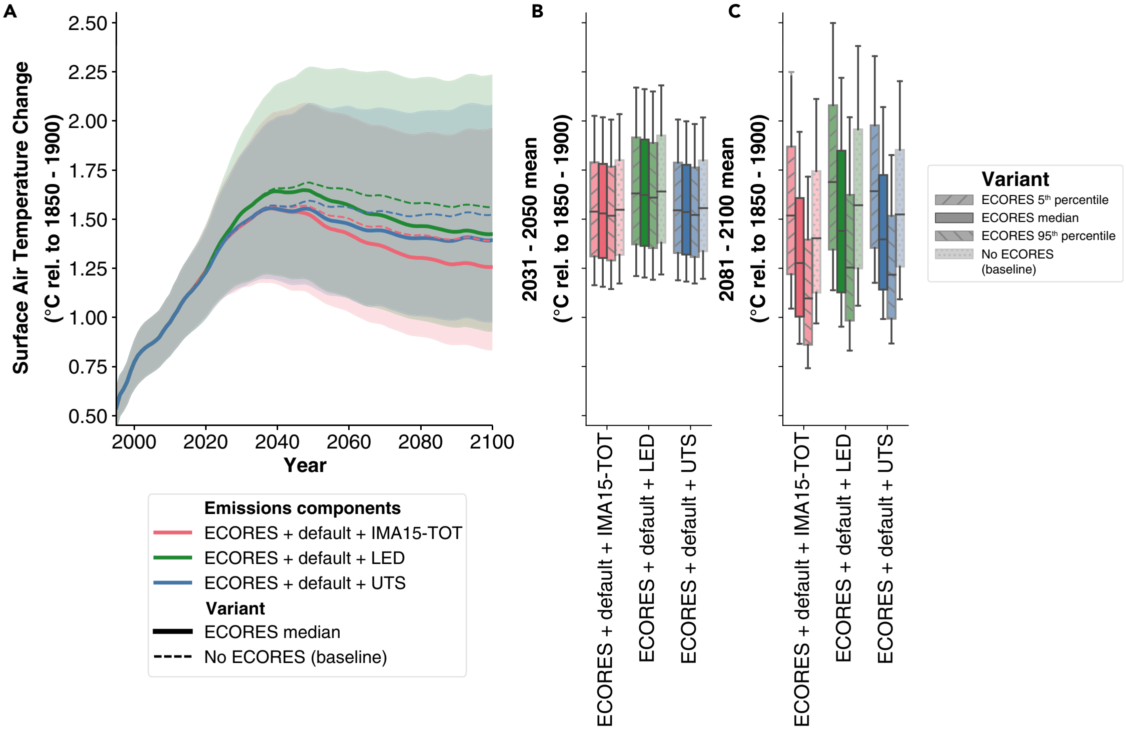

Figure 3. Temperature pathway for RESTORE scenario

(A) Removals from ECORES are combined with emissions from default land-use baseline and three different decarbonization scenarios. In all cases, median temperature briefly exceeds 1.5°C before declining to between 1.25°C and 1.5°C by 2100. The solid line depicts the median, while the shaded areas show the 5th–95th percentile range. The dashed lines depict the projections when no ECORES solutions are included in the scenario (no shaded area, only median output shown).

(B and C) There is little difference in temperature impacts for the 2031–2050 mean (approximately the time of peak global temperature) over the range of removal estimates (B). Also shown are 2081–2100, i.e., end-of-century temperatures, highlighting that the uncertainty from our removals translates into an ~0.5°C difference in end-of-century temperatures (C). The solid black line shows the median, the boxes show the 17th–83rd percentiles, and the whiskers show the 5th–95th percentiles.

deforestation could cause significant warming given that the above-ground carbon stocks in primary tropical forests alone (104–118 GtC)[35] are roughly equivalent to the remaining global carbon budget at ~109 (136) GtC from 2020 for a 66% (50%) probability of limiting global warming to 1.5°C above pre-industrial levels.[42]

DISCUSSION

Temperature pathway and probabilities

Achieving a lower peak in temperature (limited to or below 1.5°C) or a greater probability (66%) of realizing the pathway shown in Figure 3 would require a more rapid decline in global energy and industry emissions over the next decade than described in the three deep-decarbonization scenarios compared here. The ECORES we have considered have long-term temperature benefits, reducing warming by the end of the century in comparison with no additional land removals, but make little difference to peak temperature before 2050 because of the time it takes for removals to scale up. Therefore, limiting peak temperatures even further would require even steeper reductions in emissions from fossil fuels and land-use change in the next decade than are presented here (which are already at the most ambitious end of the existing scenario literature, such as the SR1.5 database[41] and emission reductions considered by Working Group 1 of the IPCC[43]).

An implication for limiting peak warming is that the carbon removals we have considered here cannot be used to offset ongoing emissions from fossil fuels or land-use change. Realizing additional sequestration via any form of land-based removals would take too long and not be of sufficient scale. Deployment of large-scale terrestrial ecosystem-based solutions is unlikely to be done quickly enough to compensate for further delays in reducing fossil fuel emissions, although protecting existing ecosystems has an important immediate mitigation benefit by avoiding emissions from land-use change. In the near term, ongoing fossil fuel emissions would cause more warming than a world in which those emissions never happened. If limiting peak warming is the goal, land-based removals are no substitute for avoiding the emissions in the first place.

The significant but ultimately limited contribution of enhancing the terrestrial biosphere to avert global warming has been recognized for some time given that fossil fuel emissions are the major determinant of atmospheric CO_2 concentrations.[44,45] Yet there remains a disconnect between science and policy on the role of terrestrial sequestration to offset ongoing emissions as part of net-zero climate mitigation pathways. The three energy scenarios compared here require 2050 fossil and energy emission reductions of 85%–98% relative to today. In other words, the vast majority of emissive activities must be ceased if we are to

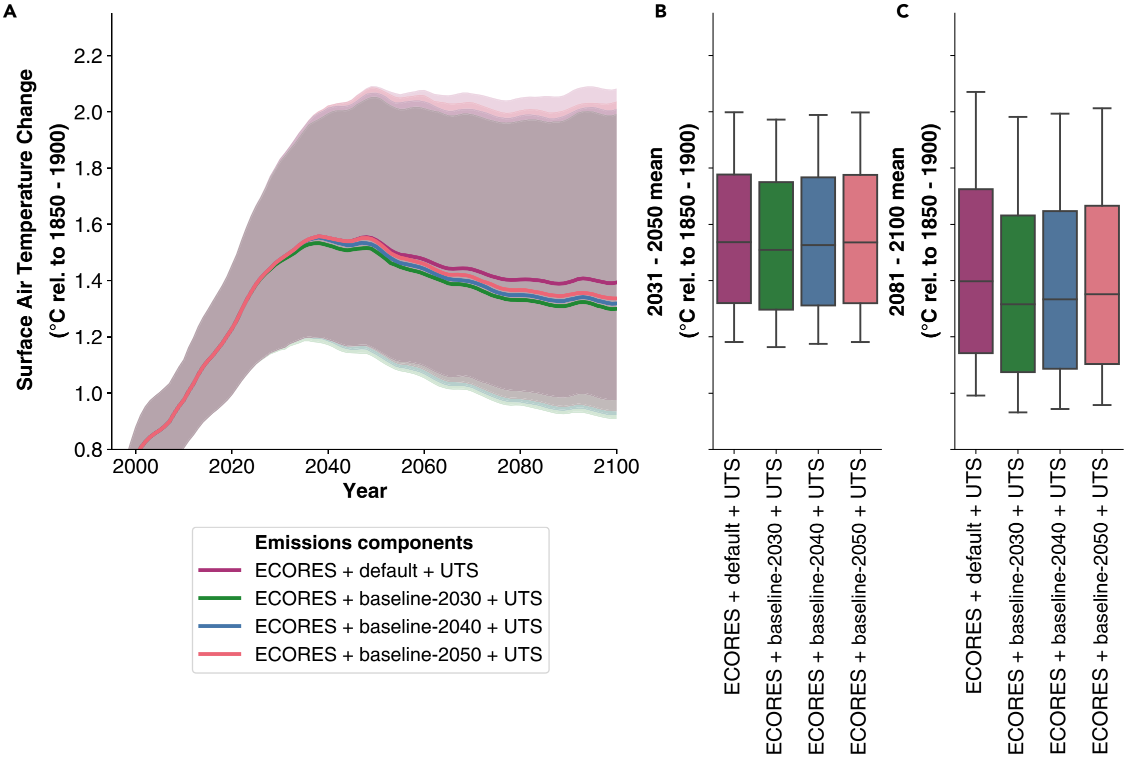

Figure 4. Temperature pathway when ECORES are combined with four different land-use baselines

(A) Four different temperature outcomes when ECORES are combined with a default land-use baseline that does not reach net zero and baselines where deforestation is halted and land-use emissions reach net zero by 2030, 2040, and 2050. The UTS scenario is used for energy and industry decarbonization. In all cases, median temperature briefly exceeds 1.5°C before declining to between 1.3°C and 1.4°C by 2100. The solid line depicts the median, while the shaded areas show the 5th–95th percentile range.

(B and C) Temperature impacts by mid-century (B) are negligible in comparison with the reduced warming of approximately 0.08°C by the end of the century (C) for the earliest deforestation phase out (default-2030). The solid black line shows the median, the boxes show the 17th–83rd percentiles, and the whiskers show the 5th–95th percentiles.

follow an approximately 1.5°C pathway, while available removals are needed to achieve net-negative emissions pathways and reduce atmospheric concentrations of CO_2. Our findings are consistent with other recent work,[13] showing that reducing peak warming by at least 0.1°C relies on steeper reductions in fossil-fuel-based emissions than are currently planned.

Approaches to land-based mitigation options

While not contributing to a reduction in peak warming, ecosystem restoration still makes an important contribution to reducing warming over the century and brings significant ecological benefits.[45] Yet the understanding that terrestrial sequestration can contribute to low-temperature pathways is not enough to inform what are the most responsible land-management options to contribute toward climate mitigation goals. Just as it is no longer tenable to lump distinct CDR methods together,[46] this also applies to different types of land-based CDR options.

Importantly, all ECORES presented here are coupled with an assumption of ending further loss and degradation of primary forests by 2030, 2040, or 2050. This brings an immediate mitigation benefit of ending net land-use change emissions, which average between 0.9 and 2.3 GtC per year over the past decade[47] and are primarily the result of tropical deforestation.[48] Without ending forest loss, these ongoing emissions from deforestation will counteract any benefits from increased sequestration. Primary forests and other intact ecosystems are irreplaceable for sustaining biodiversity.[49] Biodiversity, in turn, underpins ecosystem health and hence the resilience of stored carbon stocks, which in carbon-dense ecosystems, such as primary forests, are irrecoverable on timescales that matter for climate mitigation.[17,35,50] Hence, ending loss and degradation of primary forests and other intact ecosystems is crucial to climate mitigation strategies[35,51]—more crucial, we would argue, than increasing removals.

To support further understanding of land-based CDR options with strong benefits for biodiversity and people, studies quantifying carbon removal could better differentiate forest cover types—primary from secondary forests, plantation from natural regrowth forests, and forest age class—as seen in some recent maps of forest carbon fluxes.[22,52,53] Going beyond forest carbon flux to more comprehensively map forest types would contribute to a better understanding of the quality of standing carbon stocks and to prioritize interventions on ecosystem restoration. While improved data in these areas will not give greatly different results in terms of century-long temperature effects, they will help to inform policy decisions over where, when, and how to restore degraded forests and other landscapes. Indeed, improved quality in maps of land-cover and land-use change and in methods to reduce uncertainties in the quantification of terrestrial carbon stocks require attention given the growing importance of land in climate mitigation strategies.[25]

Feasibility

The discussion around feasibility of large-scale ecosystem restoration largely hinges around costs, such that the inherent trade-offs between production and restoration represent an opportunity cost.[15]

Crucially, any proposal to halt deforestation relies on minimal to no future expansion in agricultural land, the leading driver of forest loss.[54] At the same time, it is critical that restoration efforts do not conflict with growing demands for food production.[55] A number of restoration frameworks have been proposed to guide policy decisions by minimizing trade-offs between ecological restoration and production,[15] assessing optimal land use between carbon storage and growing food,[56] or incorporating a socio-ecological systems framework into restoration planning to include local social contexts.[57] Compared with biophysical criteria alone, incorporating a socio-political context alters the selection of priority areas.[57] Ensuring that collective tenure systems and land rights are respected and strengthened is also critical to conserving intact forests and ecosystems.[58,59] Decision-making frameworks such as these, applied at national and local scales, are ultimately required for land-restoration decisions to meet multiple sustainability objectives and align with a rights-based approach.

The most significant barrier to feasibility in the pathways presented here is the proposal to reduce harvest in natural forests (25% in boreal and temperate regions and 100% in the tropics), which would bring significant economic impact to forestry industries. Achieving such a reduction while still meeting timber demand would rely heavily on reducing overall wood product use through increased efficiency, recycling, and less consumption to avoid an expansion of forest plantations. Timber production is more efficient in plantations, and so demand can be met from a smaller land area than with native forest harvest.[60] Increasing production and use efficiencies, along with reducing wasteful consumption and finding alternatives to wood products,[61] has the potential to meet growing demand for timber without increasing wood production.[62] The Food and Agriculture Organization (FAO) reports a trend of increasing efficiencies in wood use, such as a shift from sawn products to composite timber products, expanded recycling, and higher recovery rates.[63]

Funding nature's contribution to climate, land-degradation, and biodiversity targets could require a tripling in investments by 2030.[64] While the upfront costs of ecosystem restoration must be supported, the majority of restoration projects can provide net benefits over longer timescales.[65] The land-management approaches of ecosystem restoration taken in this study fall into what has been classified as lower-cost options (forest restoration and cropland and grassland regeneration) compared with higher-cost restoration opportunities, such as coral reefs and coastal and inland wetlands.[65,66]

Conclusion

With the increasing focus on nature as a "climate solution," it is critical to understand the contributions that land-based mitigation can make to limiting temperature rise when removals are constrained to prevent perverse impacts on other environmental and social objectives. Our responsible development approach to increasing carbon sequestration through land-management interventions resulted in a median of 103 GtC of carbon removal over the century, which is considerably less than studies assessing the biological potential. When combined with deep-decarbonization pathways to assess the temperature impact of these removals, we find that ecosystem restoration makes a long-term contribution to reducing warming over the century (median of 0.1°C) but makes little difference to peak temperature given that realizing any form of land-based CDR takes decades. The upper end of our removal range, with roughly double the removals and in line with recent literature estimates, still has only a marginal impact on peak warming over the next few decades (although 2100 temperatures are reduced by 0.25°C at the upper end of the range).

The significance of these results is twofold: first to build consensus on estimates for CDR potential per hectare, activity type, and location and more importantly to serve as a "reality check" on the contribution that land-based removals can make to reducing global warming in comparison to phasing out fossil fuel emissions. It is important to consider that current policy projections put us on track for 3°C of warming. Our results here show that improved land-management options can lower peak temperatures by approximately 0.01°C and end-of-century temperatures by approximately 0.1°C. In other words, deploying all of the removal options considered here under a current policy scenario would lower peak warming to 2.99°C and end-of-century warming to 2.9°C (likely even less because carbon-cycle feedbacks are likely to be stronger in a 3°C world than they are in the 1.5°C scenarios considered in our analysis). Clearly, if we are to meet the goals of the Paris Agreement then such land-management options are not the entire solution; large departures from fossil fuel use compared with current policies are the most important factor. While nature restoration is an important mitigation option over the century, it does not play a significant role in limiting peak global temperatures. This exploration of the time dimensions of assessing mitigation benefits of different activities or pathways serves as an important reminder that land-based removals are no substitute for avoiding emissions in the first place.

However, poor management of the land sector would also push the Paris Agreement goals out of reach. We must preserve existing forests and ecosystems, which contain vast quantities of carbon stocks, and continue to remove carbon from the atmosphere while restoring ecosystems and phasing out fossil fuel emissions. We suggest that feasible approaches to CDR via land-based mitigation options must be based on a responsible development framing that includes broader social and environmental objectives. The five ECORES presented here, while lacking the necessary local social context for policy development, reflect principles of ecological restoration and highlight the need for frameworks to assess trade-offs, competing land uses, and local needs and rights when developing restoration objectives.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Kate Dooley (kate.dooley@unimelb.edu.au).

Materials availability

This study did not generate new unique materials.

Data and code availability

All data required for reproducing this study have been deposited at Zenodo: https://doi.org/10.5281/zenodo.5571116 and are publicly available as of the date of publication. All original code has been deposited at Zenodo: https://doi.org/10.5281/zenodo.5571116 and is publicly available as of the date of publication. The code is also openly available at https://gitlab.com/znicholls/one-earth-2022. Any additional information required for reanalyzing the data reported in this paper is available from the lead contact upon request.

Quantification of ECORES

In contrast to Littleton et al.,[21] who take a spatially explicit approach and use a DGVM, here we use an area-based (statistical) representation of land area and a bookkeeping approach to quantify the carbon-removal potential. The different methodological approaches build consensus on estimates of ecosystem-restoration potential via these land-management options.

For each of the five ECORES (see Table 2 for descriptions), we employed statistical datasets from the FAO to determine land area.[67,68] The FAO reports forested land under the categories of primary forest, planted forest, and naturally regenerating forest, the last of which includes the sub-categories of production forests and multiple-use forests, among others.[67] For forest restoration, it was assumed that 25% (449 Mha) of currently logged forests (production forests and multiple-use forests) are set aside for conservation purposes and allowed to regrow (Tables S2 and S4). Primary forest areas and existing conservation areas were excluded from this on the assumption that these areas are not degraded. The remainder of multiple-use and production forests in temperate and boreal regions were assumed to see a 25% decrease in production intensity under the reduced harvest pathway, equivalent to logging ceasing over 221 Mha, whereas in tropical and subtropical regions, timber harvest was assumed to cease altogether (over 532 Mha) (Tables S2 and S3).

Two of the land-management pathways rely on regeneration of agricultural land: agroforestry and silvopasture. Land areas were based on FAO area data on cropland and permanent meadows and pastures,[68] and it was assumed that shrubs and trees were increased on 20% of cropland and 10% of pastureland (Tables S6 and S7), well below literature estimates for suitable land areas for these practices.[69,70]

The reforestation pathway is the only land-management intervention in this scenario that requires a change in land use. We based the estimates for this pathway on current government pledges under the Bonn Challenge, a global initiative to restore 350 Mha of forests by 2030.[26] Currently, a total of 212 Mha (192 of which are in tropical regions) have been pledged. By basing estimates of sequestration potential on existing Bonn Challenge pledges, we are relying on national government assessments of land availability.

To quantify the sequestration potentials that are implied by the five ECORES pathways, we developed an ensemble of carbon-removal estimates based on median estimates of the maximal annual sequestration rates and their levels of uncertainty for different climatic biomes and activities sourced from the literature.[22,35,71] We assume that after a certain phase-in period for regenerative activities (reforestation, agroforestry, and silvopasture), this maximal annual sequestration rate can be reached and sustained for a number of years, whereas for activities reliant on ending degradation (forest restoration and reduced harvest), maximal sequestration rates are reached after a non-additional return period (assumed to be 20 years). 20 years is based on the change in emission-removal factors from young-secondary to old-secondary at 20 years. While old-growth forests continue to sequester carbon,[33] our model assumes that after a certain "saturation period," sequestration rates decline back to zero. While mature forests continue to sequester carbon, this is part of the residual carbon sink. Here, we are intending to quantify only additional uptake that could be considered part of the anthropogenic carbon sink. Drawing this distinction here is widely acknowledged as difficult, but an effort must be made to define additionality when quantifying carbon removals as part of mitigation efforts. The forest restoration and reduced harvest pathways also resulted in reduced emissions from forest degradation. We calculated these by applying emission factors (from Harris et al.[22] but reduced by 35% in line with an average value for carbon-density reduction through degradation)[35] to the total area under these two pathways.

We derive our ensemble via a basic Monte Carlo method. For each parameter in the calculation of removal over time, we create a skewed normal distribution (a combination of a normal and log-normal distribution) that represents the mean and 95th percentiles (as given in Table S1). For the tropical regions, we sum the uncertainties from the tropical and subtropical domains (by conservatively assuming perfect correlation of errors) to arrive at the uncertainty for our tropical domain. We then make 3,000 independent draws from each parameter distribution and use them to create 3,000 removal time series for each pathway in each climatic domain. For each time series, we check that the cumulative carbon removal is capped by the maximum natural carbon carrying capacity of the ecosystem.[35,71] If carbon removal exceeds the maximum, we shorten the saturation period. If carbon removal exceeds the maximum, even after we reduce the saturation period to zero, we then shorten the phase-in and phase-out periods equally (and as a result reduce the maximum removal) until we are below the maximum cumulative carbon removal. Finally, we downscale to the regional (R5) level by using each region's share of the total area available for each pathway in each climatic domain (by using the FAO land areas as described above).

For uncertainties in maximum flux rate (removal factors) for existing and new forest, we use data from Harris et al.[22] (data supplied by the authors[1]). We calculate the 67% confidence interval by taking the square root of the variance. For the tropical regions, we sum the uncertainties from the tropical and subtropical domains (by conservatively assuming perfect correlation of errors) to arrive at the uncertainty for our tropical domain. This applies to the max flux rate in reduced harvest in the tropical biome (Table S2), forest restoration in all biomes (Table S3), and reforestation in temperate and tropical biomes (Table S4). The maximum flux rate (removal factors) for existing forest in temperate and boreal biomes under the reduced harvest pathway (Table S2) follows an existing method,[29] where the flux rate is calculated as the difference in carbon stock between a degraded forest and the maximum carbon carrying per hectare (available carbon density per hectare) divided by the recovery time. Uncertainty values for the flux rate are based on the variance of available carbon density per hectare.[71]

Deriving temperature outcomes

Probable temperature outcomes are derived when the ECORES pathways are combined with deep-decarbonization pathways in line with updated carbon budgets and projected land-use trends. A land-use baseline is drawn from scenarios modeled under the shared socio-economic sustainability future (SSP1)[41] and represents CO_2 emissions from forestry and land use (including land-use change) in the absence of the ecosystem-restoration measures considered here. To minimize the risk of double-counting sequestration, we also remove all carbon sequestration reported in the land-use baseline. We consider three alternative land-use baselines, representing halting of deforestation by 2030, 2040, and 2050. We combine these land-use pathways (baselines and ECORES) with three deep-decarbonization scenarios selected from the literature: a transition to 100% renewable energy,[39] a LED scenario,[2] and renewable energy and efficiency options coupled with significant behavior changes.[40] The resulting family of three scenarios, which we call RESTORE, briefly exceeds 1.5°C (median temperature) before declining to between 1.25°C and 1.5°C by 2100 under all modeled energy-demand and land-use baseline conditions. Updated input data (land area, carbon flux, and carbon budgets) increase the relevance of these findings in comparison with previous work.

To derive temperature outcomes, we require not only the carbon removal from our ecosystem-regeneration pathways but also a land-use baseline pathway and carbon emissions from fossil fuel sources, as well as non-CO_2 emissions. Input emissions and resulting temperature outcomes for all scenario options are openly available (see "data and code availability").

The land-use baseline pathways represent CO_2 emissions from forestry and land use (including land-use change) in the absence of the ecosystem-restoration measures considered here. We create four land-use baseline pathways.

Our default land-use baseline pathway is based on the IMAGE model's quantification of the SSP1-baseline scenario in the SR1.5 database.[41] We use SSP1-baseline due to its compatible assumptions around reductions in deforestation, minimal land-use change, transition to more sustainable diets, and low bioenergy demand.[72] To minimize the risk of double-counting sequestration, we also remove all carbon sequestration reported in the SSP1-baseline scenario. On the basis of this as a default land-use baseline, we create three additional pathways. The first diverges from the default pathway in 2020 and reaches net-zero land-use emissions in 2030 (labeled default-2030). The second and third diverge from the default pathway in 2030 and 2040, respectively, reach net-zero land-use emissions in 2040 and 2050, respectively, and are labeled default-2040 and default-2050, respectively. These three additional baseline land-use pathways represent halting deforestation by 2030, 2040, and 2050.

We combine our ecosystem-restoration and land-use baseline pathways with three deep-decarbonization pathways for CO_2 emission from energy and industrial sectors and non-CO_2 emissions from the literature. The first is the LED scenario.[2] The second presents alternative pathways for 1.5°C (IMA15-TOT).[40] The third is a rapid energy-transition pathway (UTS).[39]

We harmonize the scenarios (combination of ecosystem restoration, land-use baseline, and decarbonization scenario for energy CO_2 and non-CO_2 emissions) to historical emissions estimates from CMIP6, as quantified in the RCMIP protocol.[73–80] While these emissions estimates do not perfectly reflect emissions trends over the past 5 years, the impact of this difference, particularly the COVID-19 blip, on decadal temperature projections is of the order of hundredths of a degree[81] and hence can be ignored (although the COVID-19 blip is captured by the UTS pathway). Net land-use emissions remain within reported ranges.[47] Assumptions about continued removal of land sinks under low-emissions scenarios are embedded in calculation of remaining carbon budgets.

Our temperature outcomes are calculated with MAGICC v7.5 in a probabilistic setting that reflects the assessed uncertainty ranges from the IPCC's Sixth Assessment Report (for complete quantification, see Cross-Chapter Box 7.1 in Chapter 7 of AR6 WG1[82]). The probabilistic setting used here results in temperature outcomes consistent with the quantification presented in Chapter 5 of AR6 WG1.[42] However, MAGICC v7.5's transient climate response to cumulative carbon emissions (TCRE) is slightly higher than the assessment, so these temperature quantifications could be viewed as being slightly (of the order of hundredths of a degree) conservative. These slightly conservative temperature quantifications can lead to carbon budgets around 50–100 Gt CO_2 smaller than reported in Chapter 5 of AR6 WG1[42] (if we assume a TCRE around 0.45 K/TtCO_2). Having said this, a difference of 50–100 Gt CO_2 is well within the uncertainty due to non-CO_2 response and scenario uncertainty of around 220 Gt CO_2 reported by WG1 of AR6.[42] Hence, it is likely that the differences between our results and the carbon budgets reported by AR6 are also due to slightly different assumptions about non-CO_2 mitigation between our scenarios and the median used by WG1 AR6.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.06.002.

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AUTHOR CONTRIBUTIONS

Conceptualization, K.D.; methodology, K.D., Z.N., and M.M.; software, validation, formal analysis, and data curation, Z.N.; investigation, K.D. and Z.N.; writing – original draft, K.D.; writing – review and editing, K.D., Z.N., and M.M.; visualization, Z.N.; funding acquisition, K.D.; supervision, M.M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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