communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-022-00391-z

OPEN

Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario

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Meeting the Paris Agreement's climate objectives will require the world to achieve net-zero CO_2 emissions around or before mid-century. Nature-based climate solutions, which aim to preserve and enhance carbon storage in terrestrial or aquatic ecosystems, could be a potential contributor to net-zero emissions targets. However, there is a risk that successfully stored land carbon could be subsequently lost back to the atmosphere as a result of disturbances such as wildfire or deforestation. Here we quantify the climate effect of nature-based climate solutions in a scenario where land-based carbon storage is enhanced over the next several decades, and then returned to the atmosphere during the second half of this century. We show that temporary carbon sequestration has the potential to decrease the peak temperature increase, but only if implemented alongside an ambitious mitigation scenario where fossil fuel CO_2 emissions were also decreased to net-zero. We also show that non-CO_2 effects such as surface albedo decreases associated with reforestation could counter almost half of the climate effect of carbon sequestration. Our results suggest that there is climate benefit associated with temporary nature-based carbon storage, but only if implemented as a complement (and not an alternative) to ambitious fossil fuel CO_2 emissions reductions.

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An increasing number of countries, cities, and corporations are committing to net-zero greenhouse gas emissions targets in an effort to contribute to achieving the climate goals of the Paris Agreement[1,2]. Alongside these targets, there is increased attention on possible strategies to remove carbon dioxide from the atmosphere (so-called carbon dioxide removal or CDR)[3–5] which would be required to reach a global net-zero target if we do not succeed in eliminating all sources of emissions[1]. Among CDR approaches, nature-based climate solutions (NbCS)[6–9] encompass a range of strategies aimed at preserving and enhancing carbon storage in ecosystems and on agricultural lands. A key appeal of NbCS is the potential to contribute to climate mitigation efforts, while also generating additional co-benefits for human well-being and biodiversity[10].

NbCS include efforts to avoid additional land-use carbon emissions (e.g., by preventing additional deforestation), as well as enhance natural carbon removal processes (e.g., by reforestation of previously deforested areas)[6–8]. To contribute to climate mitigation efforts, NbCS would need to slow the carbon loss from, and subsequently increase the amount of carbon stored in, natural systems. To contribute specifically to achieving net-zero emissions targets, NbCS would need to achieve net carbon removal from the atmosphere beyond what would be achieved via natural processes only. To further contribute to limiting climate warming, we also need to ensure that NbCS do not have additional climate effects that might counter the climate benefit of enhanced carbon sequestration[11]. And in all cases, the timescale over which carbon remains stored in nature is likely a key determinant of its net climate benefit.

Previous analyses of the global potential of NbCS have suggested that a combination of avoided land-use CO_2 emissions and enhanced carbon sequestration in natural systems could provide more than one-third of the mitigation effort between now and 2030 that would be needed to stabilize warming below 2 °C[6]. This positioning of NbCS-based mitigation activities as equivalent to and interchangeable with fossil fuel CO_2 emissions reductions carries an implicit assumption that the removed (or not emitted) carbon will be permanently sequestered. This is a critical assumption that has not been well acknowledged in the literature to date; indeed, anything less than permanent storage would result in only a temporary climate benefit that would not match the multi-century to millennial-scale warming caused by fossil fuel CO_2 emissions[12,13]. However, the permanence of carbon storage in natural ecosystems cannot in reality be guaranteed, given its vulnerability to both human-driven (e.g., deforestation or other land-use change) and climate-related (e.g., wildfire, drought, or insect) disturbances that could occur at any time in the foreseeable or unforeseeable future[14–19]. Quantifying the near-term carbon sequestration potential of NbCS[6,9,20] is therefore not sufficient to gauge the potential contribution of NbCS to the long-term temperature goal of the Paris Agreement. Rather than assuming permanent storage via NbCS, we should in fact assume that some or all of this carbon storage will be temporary and then ask: to what extent will temporary carbon sequestration via NbCS contribute to meeting our climate mitigation goals?

Here we assess and quantify the climate and carbon cycle implications of nature-based carbon removal resulting in temporary storage in land ecosystems, when implemented alongside Shared Socioeconomic Pathway (SSP) climate mitigation scenarios. We use two scenarios which span a plausible range of future mitigation ambition, from relatively weak (SSP2-4.5, with continued CO_2 emissions through 2100) to very strong (SSP1-1.9, with CO_2 emissions reaching net-zero by mid-century) (See Methods). We use an intermediate-complexity global climate model[21] to simulate the near-term rate of temperature increase, the peak temperature change, and the long-term temperature trajectory in response to a set of emissions scenarios which include both global decarbonization efforts and temporary land-based enhanced carbon storage (see Methods). We simulated land-based sequestration first as an idealized scenario with prescribed CO_2 removal and second using the model's dynamic vegetation component to simulate an expansion of global forest cover. In both cases, the modeling setup reflects a case where NbCS are used to withdraw carbon from the atmosphere over the next three decades, followed by the stored carbon being gradually released back to the atmosphere during the second half of this century.

Results

Idealized temporary carbon removal. We implemented three idealized NbCS scenarios based on estimates of the feasible potential of NbCS-based carbon removal[6,22], in which we prescribed an increasing rate of removal beginning in 2020, and reaching a maximum removal rate at 2030 of 3.64[22] and 10.4[6] $GtCO_2$ per year relative to the baseline scenario emissions (see Methods). In two of the scenarios, we then decreased this rate of removal after 2030 to zero at the year 2056, resulting in cumulative removals of 81 and 173 $GtCO_2$ in the two scenarios; in the third, we sustained the higher removal rate of 10.4 $GtCO_2$ per year until the year 2050 before decreasing it to zero at 2056, leading to a cumulative removal of 316 $GtCO_2$ (Fig. 1a, d). In all three scenarios, this removed carbon was subsequently fully or partially (50%) returned to the atmosphere after 2056. In the case of full return of removed carbon, cumulative CO_2 emissions at the year 2100 were equivalent to the baseline SSP scenarios, whereas the 50% return scenarios led to slightly lower cumulative emissions at 2100. In response to this temporary carbon removal, mid-century atmospheric CO_2 concentrations were decreased by between 7 and 28 ppm across the two SSP and three carbon removal scenarios (Fig. 1b). This represents a carbon removal effectiveness of between 63 and 69% (i.e., between 31 and 37% of the removed CO_2 was offset by reduced carbon uptake by the land and ocean carbon cycle).

Given the absence of any biophysical land-surface changes in these simulations, the global temperature response to this prescribed temporary carbon removal was closely proportional to the change in cumulative CO_2 emissions, reaching a maximum difference of between 0.04 and 0.17 °C below the temperatures in the SSP baseline scenarios (Fig. 1c). This represents a global temperature response of between 0.5 and 0.55 °C per 1000 $GtCO_2$ removal, similar to that found in previous idealized carbon removal experiments using this model[23]. In the case of the SSP1-1.9 scenario, this difference led to a decreased peak temperature level of between 0.03 and 0.07 °C (Fig. 1e), whereas for SSP2-4.5 temperatures did not peak during the 21st century and the effect of temporary carbon removal was rather to delay the occurrence of a particular level of warming: by 0 to 1 year for 1.5 °C and by 2 to 8 years for 2 °C (Fig. 1c). For both scenarios, the annual warming rate between 2020 and 2050 decreased in response to the prescribed carbon removal, with subsequently higher rates during the second half of the century. Both global temperature differences and changes to the rate of warming were temporary effects in our simulations. The full return of removed carbon caused the temperature to return to the level of the baseline SSP scenarios shortly after the year 2100, whereas partial (50%) return led to end-of-century temperatures that remained between 0.02 and 0.08 °C below the baseline scenario temperatures at the year 2100.

Reforestation-based temporary carbon removal. The simulations presented in Fig. 1 show the potential climate response to a prescribed temporary carbon removal scenario, but do not

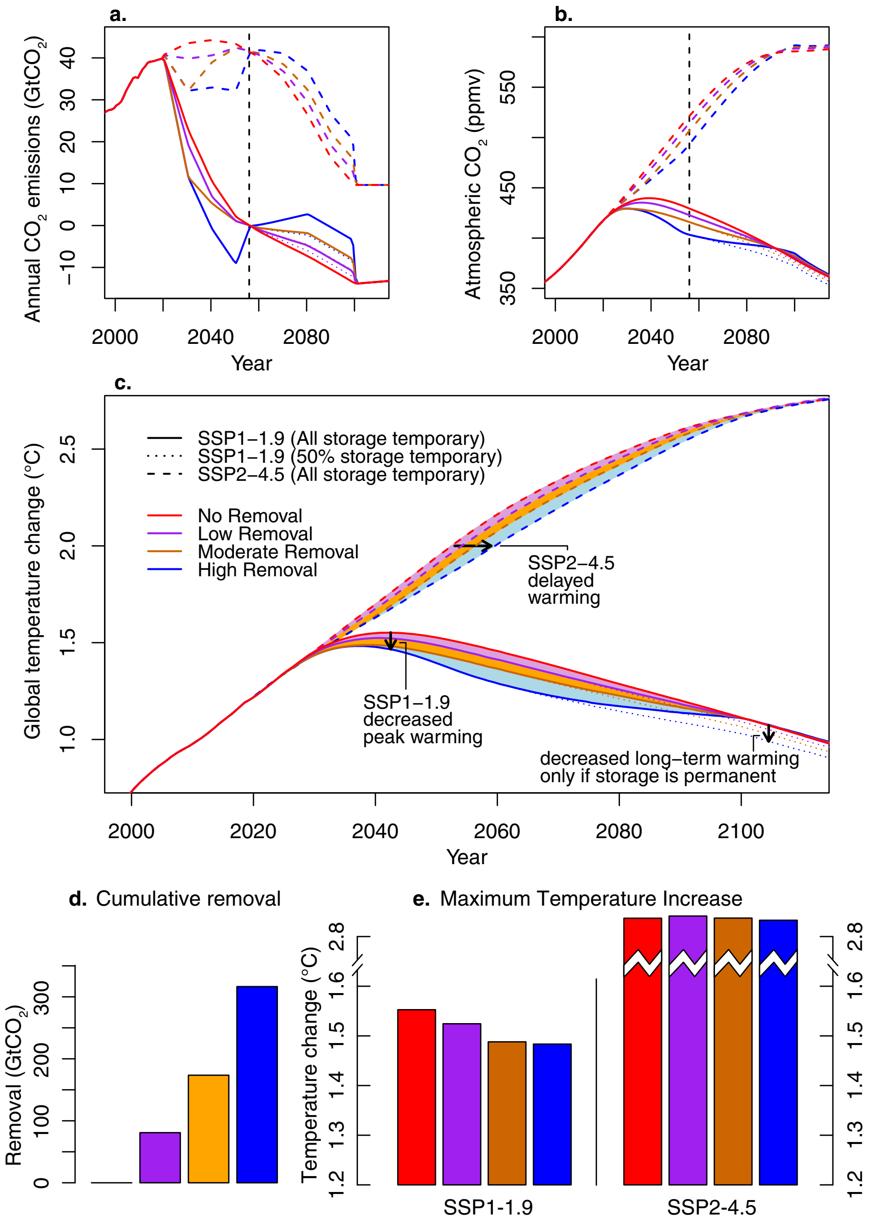

Fig. 1 Climate response to prescribed temporary carbon removal scenarios. **a**, **d** Prescribed CO_2 removal and subsequent full or partial (50%) return to the atmosphere resulted in cumulative temporary removals of 81 (purple lines/bars), 173 (orange lines/bars), and 316 (blue lines/bars) $GtCO_2$ relative to the baseline scenarios (red lines/bars). **b** Atmospheric CO_2 decreased by maximum amounts of 7 to 28 ppm across scenarios in response to the prescribed removal. **c**, **e** Global temperatures decreased by a maximum amount of 0.04 to 0.17, relative to the baseline SSP scenarios, and in the SSP1-1.9 scenario peak temperatures decreased by between 0.03 and 0.07 °C. The effect on long-term temperature in the SSP1-1.9 scenario depended on the longevity of the stored carbon: fully temporary storage (solid lines in panels **a**–**c**) caused temperatures to return to the baseline scenario temperature by the end of the century, whereas if 50% of the stored carbon was assumed to be stored permanently (dotted lines), the effect on global temperature was similarly sustained.

represent any particular type of NbCS, many of which would have additional effects on climate beyond the removal of CO_2[9,11]. In the case of NbCS that lead to vegetation cover changes, these additional biophysical effects would include modified surface albedo, evapotranspiration, and surface roughness, as well as effects on atmospheric circulation and cloud characteristics[24–27]. In particular, forest-based NbCS such as afforestation and reforestation have the potential to affect climate via all of these biophysical mechanisms in addition to the effect of carbon sequestration[6,9,26,28–30]. Here, we assessed the specific case of a temporary reforestation-based NbCS scenario, in which we allowed forest distributions in the model to regrow to their historical (the year 1920) extent between 2020 and 2056, and then gradually returned forest cover to their SSP scenario-projected distributions between 2056 and 2100 (see Methods). Modeled results, therefore, included both a temporary removal of atmospheric CO_2 and the associated biophysical changes resulting from simulated forest cover changes. In the climate model used here, these biophysical effects include surface albedo, evapotranspiration, and roughness length changes, but not changes in cloud cover whose distribution is a prescribed and non-dynamic component of our atmospheric model.

Our SSP1-1.9 forest regrowth scenario led to an increase of approximately 3.6 million km^2 of increased forested area in the

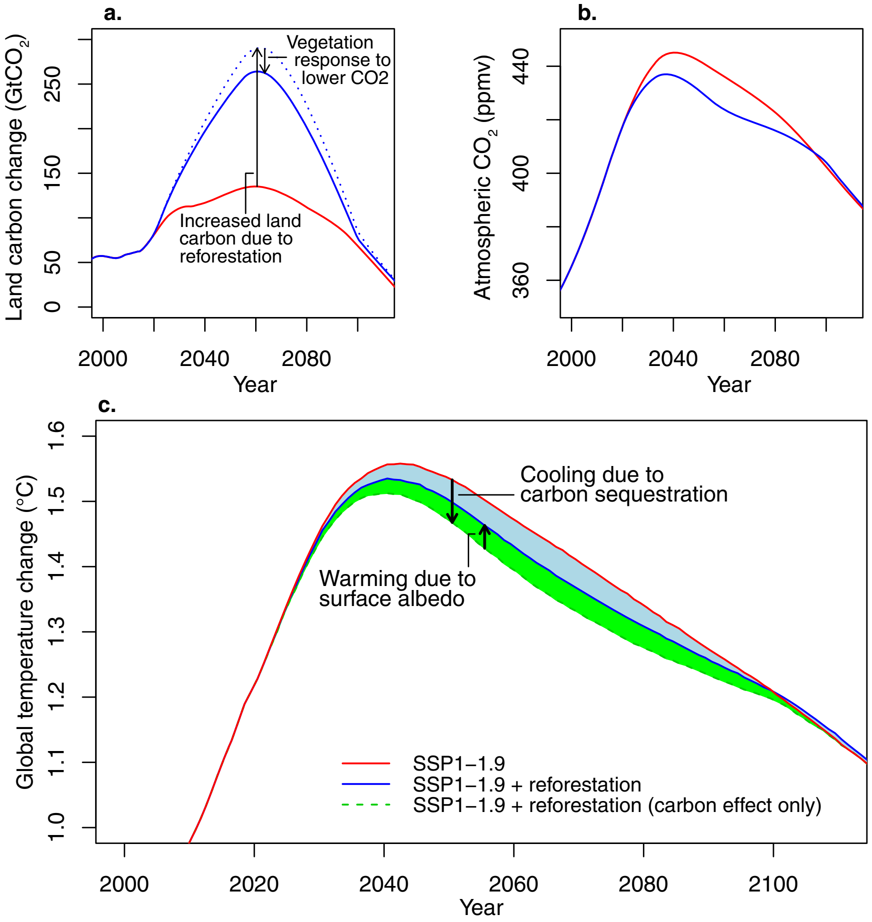

Fig. 2 Climate response to a temporary reforestation-driven carbon removal scenario. **a** Reforestation to the year 1920 forest extent led to an additional 129 $GtCO_2$ of land carbon storage relative to the baseline SSP1-1.9 scenario, which was subsequently returned to the atmosphere during the second half of this century. **b** Atmospheric CO_2 concentrations decreased by 12.3 ppm in response to this increase in land carbon storage. **c** Peak temperature in this scenario decreased by 0.022 °C, with the maximum temperature decrease relative to baseline scenario reaching 0.045 °C around the year 2060. The primary biophysical effect of expanded global forest cover was to decrease land surface albedo, which consequently decreased the climate response to reforestation by about 45% relative to the temperature change that would have occurred in response to only carbon sequestration.

model, resulting in an additional land carbon storage of 129 $GtCO_2$ at mid-century relative to the no-regrowth scenario (difference between blue and red lines in Fig. 2a). This sequestered carbon was subsequently returned to the atmosphere by the year 2100 in response to the prescribed return to scenario-projected forest cover distributions at the end of the century. Interestingly, the land carbon increase simulated here was the result of two opposing processes in the model. Reforestation alone would have resulted in an additional 156 $GtCO_2$ of land carbon increase (dotted blue line in Fig. 2a; see Methods). However, the resulting decrease in atmospheric CO_2, which reached a maximum of 12.3 ppm below the baseline CO_2 concentration (Fig. 2b), caused land vegetation everywhere in the model to sequester less carbon as a result of a decreased global CO_2 fertilization effect. This vegetation feedback decreased total land carbon in the reforestation simulation by 27 $GtCO_2$ (difference between the dotted and solid blue lines in Fig. 2a), resulting in a net land carbon increase of 129 $GtCO_2$ (solid blue line in Fig. 2a).

The global temperature response to this reforestation-based carbon removal scenario was considerably less pronounced than in the idealized removal scenario on account of the biophysical effects (most notably the surface albedo decrease) caused by expanded forest cover (Fig. 2c). The temperature difference caused by reforestation reached 0.045 °C at the time of maximum forest carbon increase, and peak temperatures in this simulation were 0.022 °C lower than in the baseline simulation (Fig. 2c). This represents a global temperature response to the removal of 0.3 °C per 1000 $GtCO_2$ of removal. Compared to the idealized case in Fig. 1 (0.5 to 0.55 °C per 1000 $GtCO_2$ of removal), this means that a unit removal of carbon via global reforestation in our model is about 45% less effective at decreasing global temperatures as compared to NbCS strategies that do not affect land surface albedo. Indeed, when we removed the biophysical effects from the reforestation simulation (dashed green line in Fig. 2c; see Methods) the maximum temperature difference was 0.08 °C (with a peak temperature decrease of 0.045 °C) representing equivalent global temperature effectiveness of removal as in the idealized removal simulations. This result emphasizes the potentially significant non-CO_2 biophysical effects of NbCS implementation; our model does not represent all such potential effects, however, most notably that of changing cloud cover in response to forest distribution changes which has been shown to cause a local cooling effect in response to increased forest cover[26,30]. It is likely therefore that including a more complete representation of non-carbon effects would cause temperature changes in this scenario to fall somewhere within the green shaded region of Fig. 2c, rather than following either the blue or green lines.

The magnitude of the biophysical surface albedo offset to reforestation-based carbon removal varied considerably

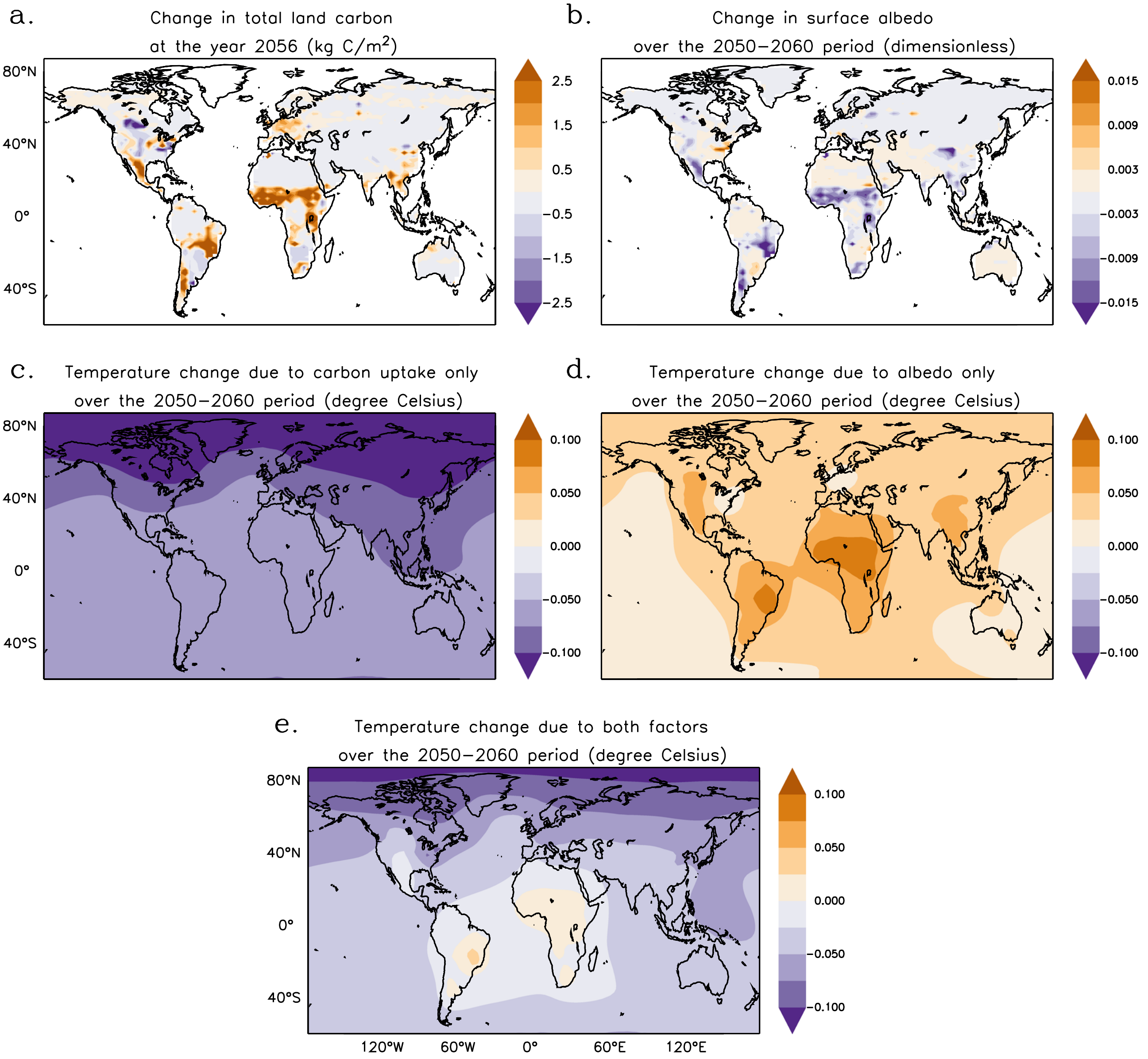

Fig. 3 Spatial pattern of climate response to carbon sequestration and surface albedo changes resulting from temporary reforestation scenarios. a Our scenario of reversed historical deforestation led to a global land carbon increase of 129 $GtCO_2$, which occurred primarily in tropical and subtropical regions. **b** The primary biophysical effect of expanded forest cover was to decrease land surface albedo in areas of significant reforestation. **d** These surface albedo decreases led to a spatial pattern of warming that was concentrated in areas of larger forest cover increase, whereas **c** the cooling due to carbon sequestration was larger at higher latitudes owing to regionally stronger climate feedbacks. **e** Consequently, the pattern of the net climate response to reforestation showed cooling over most of the land areas, but a small net warming over some tropical continental regions.

depending on where reforestation occurred in our simulation. Our scenario of a reversed historical deforestation pattern resulted in a particular spatial pattern of land carbon increase (Fig. 3a) that reflects where our model's climate would support the growth of forests in regions that were converted from natural vegetation cover to agriculture or pasture between 1920 and 2020. The resulting global land surface albedo decrease was 0.0015 (0.15 percentage points), with regional decreases of up to 0.02 (2 percentage points) in areas of high reforestation (Fig. 3b). The climate consequence of this pattern of surface albedo decreases (Fig. 3d) shows a clear pattern of regional warming localized around areas of forest carbon increase and associated surface albedo decrease. In contrast, the cooling due to only carbon sequestration (Fig. 3c) occurred globally, with larger cooling at higher latitudes owing to stronger regional positive feedbacks that amplified the response to lowered atmospheric CO_2. Consequently, though the global effect of reforestation in this model was to cool the climate, regions of the highest level of reforestation showed a small regional warming on account of a regionally larger albedo effect compared to the global effect of carbon sequestration at that location (Fig. 3e).

Discussion and conclusions

Our results show that successful carbon sequestration via NbCS can have climate benefit, even in the case that the carbon storage is temporary such that the stored carbon is returned to the atmosphere later this century. However, the most important climate benefit—a decrease in the level of peak warming—is only realized in a scenario where fossil fuel CO_2 emissions are decreased rapidly to net-zero, resulting in global temperatures that peak and decline during the time period that NbCS-stored carbon remains sequestered in nature. This implies that realizing a tangible climate benefit from NbCS will require net-zero fossil fuel CO_2 emissions to be achieved on the same timescale as the successful implementation of NbCS. In the absence of this level of stringency in future mitigation efforts, temporary NbCS-based carbon storage would not affect peak warming and would serve only to delay the occurrence of a given warming level, with no other long-term climate benefit.

Our results also demonstrate the need to better assess the potential non-CO_2 climate effects of NbCS. Here, we quantified the effect of albedo and other biophysical changes associated with global reforestation efforts, and can conclude that NbCS methods that lead to decreased surface albedo will have a reduced climate benefit. Previous discussions of NbCS options have highlighted tropical forest reforestation as a more robust climate strategy compared to high-latitude reforestation for exactly this reason[6,20,28,29]; our results suggest that even tropical forest restoration has a substantial albedo-related penalty associated with it, given that our reforestation scenario resulted in primarily tropical and subtropical forest carbon sequestration. We note, however, that our model is not able to simulate all of the non-CO_2 effects of reforestation; notably, we do not simulate changes in cloud cover, which have been shown to have a regional cooling effect in response to both tropical and mid-latitude forest cover increases[26,30]. Previous reviews of NbCS options have also highlighted wetland restoration and soil carbon sequestration as no-regrets options with few negative consequences[10]. However, wetland restoration would also change surface albedo, as well as the balance of carbon vs. methane emissions from the landscape[31]. Similarly, soil carbon sequestration could also lead to altered surface albedo, particularly if achieved via the addition of biochar[32,33]. On the other hand, there is also the potential for synergies between carbon and biophysical effects of some NbCS approaches, particularly in response to improved management practices within existing forested[34] or agricultural[35–38] landscapes. Both our analysis and the existing literature on this topic suggest a need to better quantify the full Earth-system response to both reforestation and a broader range of other NbCS approaches so as to be able to better estimate the net climate response to these proposed solutions.

Perhaps the most salient implication of our results is to challenge the prevailing narrative surrounding the role of NbCS in climate mitigation. Recent claims of the carbon storage potential of NbCS[6,7,9,20,39] have generally positioned NbCS as a contribution to climate mitigation that is interchangeable with other emission reduction options. The framing of land-based mitigation as a potential emissions-reduction wedge has been long-standing in the literature[40,41], but fails to acknowledge that the climate effect of nature-based carbon sequestration is only equivalent to a fossil fuel CO_2 emissions reduction if: (1) the carbon is permanently sequestered in nature; and (2) the additional non-CO_2 effects of NbCS are small relative to the climate benefit of carbon sequestration. Our analysis here shows that if permanence is not achieved, the climate benefit is also temporary and that this benefit has the further potential to be significantly weakened by non-CO_2 climate effects. Both findings lead us to question the wedge-based framework that positions NbCS efforts as interchangeable with fossil fuel emissions reductions. Rather, we show that the potential for NbCS to decrease peak warming depends on NbCS implementation alongside a rapid transition to net-zero fossil fuel CO_2 emissions.

There are of course many potential social and environmental benefits to investing in protecting and restoring nature, beyond carbon sequestration, which can also help mitigate climate risks[6,39,42]. Well-designed stewardship or conservation of natural systems can have immediate and direct benefits to local environmental conditions, and could also benefit local and indigenous communities[43]. Biodiversity, water, and air quality are valuable ecosystem services in and of themselves, and efforts to enhance these can also help to build community resilience to climate change[39,43,44]. Our analysis suggests that near-term carbon sequestration potential could represent an additional co-benefit among a range of other environmental and social benefits resulting from improved nature stewardship and conservation. However, the climate mitigation potential of this carbon sequestration will likely only be realized if it is treated as an addition (and not an alternative) to rapid fossil fuel emissions reductions.

Methods

We used the University of Victoria Earth System Climate Model (UVic ESCM) version 2.10[21,45], an intermediate-complexity global climate model with a spatial resolution of 3.6° longitude and 1.8° latitude. Model subcomponents include a three-dimensional general circulation ocean model with 19 vertical layers[45], a single-layer energy-moisture balance atmospheric model[45], a dynamic-thermodynamic sea-ice model[45], a land-surface and dynamic vegetation model with five plant functional types[46], and an interactive land and ocean carbon cycle[47] that includes representation of ocean sediments[12] and permafrost carbon[48]. This model is well suited to the efficient simulation of multi-century climate responses to CO_2 emissions and other climate forcings, and can additionally represent the climate response to spatial land-use changes[49]. Plant functional types in the dynamic vegetation model include needleleaf and broadleaf trees, C3 and C4 grasses, and shrubs, where agricultural cropland and pasture areas are represented by either of the two grass functional types[21,46,49]. The most notable limitation of this model is its non-dynamic atmosphere, which allows for computationally-efficient long-timescale simulations, but without dynamic representation of atmospheric circulation or cloud distributions; rather surface wind and cloud albedo fields are prescribed from observations and held fixed over time[21,45]. This model has been used and validated extensively over the past two decades to look at research questions such as assessing the effect of historical land-use change on climate, estimating the magnitude of climate-carbon cycle feedbacks, and quantifying the role of terrestrial and oceanic carbon cycle process in the context of both past and future climate scenarios[12,49–52].

Using the UVic ESCM, we simulated the temporary storage of carbon via natural climate solutions (NbCS) alongside two baseline climate mitigation scenarios. Both baseline scenarios are drawn from the Shared Socioeconomic Pathways (SSP) ensemble of future greenhouse gas concentration scenarios[53]. Here, we selected two greenhouse gas mitigation scenarios that span a plausible range of future mitigation efforts, from a scenario of continued relatively weak effort (SSP2-4.5) to one of very rapid and ambitious future emissions reductions (SSP1-1.9). The SSP2-4.5 scenario reflects a middle-of-the-road future socioeconomic pathway that is similar to current global conditions, with mitigation efforts that allow global radiative forcing to continue to increase and then stabilize at 4.5 W/m^2 at the year 2100; this scenario represents a weak climate mitigation scenario in which global CO_2 emissions peak around 2030–2040 and then decrease (but remain positive) throughout the second half of the century. SSP1-1.9, by contrast, is a future scenario of socioeconomic conditions oriented around sustainability principles, combined with a rapid acceleration of global climate mitigation efforts that succeed in lowering global radiative forcing to 1.9 W/m^2 at the year 2100; this scenario represents a highly ambitious mitigation scenario with peak CO_2 emissions at the year 2020 that decrease to net-zero at the year 2056 and then become net-negative throughout the remainder of the century[53]. Other non-CO_2 climate forcings were included in the simulations, based on observations for the historical period, and then following the forcing trajectories of SSP1-1.9 and SSP2-4.5, respectively. For both scenarios, temporary natural carbon removal was prescribed to occur between 2020 and 2056 (the net-zero year of SSP1-1.9), and this stored carbon was then returned to the atmosphere between 2056 and 2100.

We implemented this temporary carbon removal in two ways: first, as a perturbation to prescribed CO_2 emissions in the model and second by allowing forests in the model to regrow to mid-19th century distributions. In the first case, this represents an idealized implementation of natural climate solutions, with no explicit modification of either the size of the modeled land carbon pool or of the land-surface characteristics that would be associated with the implementation of particular types of NbCS. The second case reflects a reforestation-based NbCS scenario, in which carbon is sequestered by the land carbon pool, and both vegetation distributions and the associated land-surface characteristics in the model changed in response to this additional carbon storage.

Idealized carbon dioxide removal scenarios. For the first set of idealized carbon dioxide removal scenarios, we implemented carbon removal due to NbCS by adjusting prescribed fossil fuel + land-use CO_2 emissions to reflect the potential of nature-based carbon removal assessed by refs. [6,22]. Prescribed CO_2 emissions were decreased relative to the baseline scenario beginning in 2020, reaching a maximum difference of 3.64[22] or 10.4[6] $GtCO_2$ per year at the year 2030 below the baseline SSP scenario. After 2030, this maximum removal rate was gradually decreased to converge with the baseline emissions scenario at the year 2056, resulting in cumulative removals of 80.7 $GtCO_2$ and 173.3 $GtCO_2$ in the two scenarios, respectively. For the 10.4 $GtCO_2$ removal level, we also included a scenario in which this amount of annual removal was sustained until 2050 (following the projection of refs. [6,39,42]), and then decreased to zero annual removal at the year 2056, resulting in a cumulative removal of 316 $GtCO_2$. After the year 2056, this removed CO_2 was either fully (100%) or partially (50%) returned to the atmosphere by increasing prescribed emissions between 2056 and 2100 relative to the baseline scenario. In this set of simulations, spatial distributions of agricultural areas were prescribed up to the year 2020, during which time the model generated land-use CO_2 emissions as a result of the conversion of forest to agricultural (grass) plant functional types. After the year 2020, spatial distributions of agriculture were held fixed and land-use emissions were prescribed according to the baseline SSP and carbon removal scenarios described above.

Carbon removal via partial reforestation of agricultural areas. For the second set of simulations, we used the same historical model simulation up to the year 2020. After the year 2020, rather than prescribing generic carbon removal scenarios as above, we prescribed changes in agricultural areas in the model to allow the expansion of forest vegetation and subsequent terrestrial carbon removal to be simulated by the model's dynamic vegetation and carbon cycle components[21]. In the base simulation without carbon removal, we prescribed spatial changes in historical and future (scenario-determined) agricultural areas, with all other climate drivers (fossil fuel CO_2 emissions and other climate forcings) equivalent to the idealized removal scenarios above. Beginning in the year 2020, we implemented a global reforestation scenario, in which forested areas were allowed to regrow from 2020 until 2056 to return to their historical extent of the year 1920. This forest regrowth was then reversed between 2056 and 2100, returning forest cover to its scenario-projected distribution at the end of the century.

In this simulation, the carbon sequestered by reforestation was simulated as an increase in total land carbon in the model. However, the change in land carbon in the model was affected by both forest regrowth (leading to increased land carbon) as well as by the global vegetation response to the lower atmospheric CO_2 that resulted from this increased land sequestration. This latter effect led to decreased CO_2 fertilization relative to the baseline scenario such that the simulated increase in land carbon was smaller than would have been achieved by reforestation alone in the absence of the additional CO_2 concentration feedback. To separate these two processes, we performed a third simulation in which the CO_2 concentration from the baseline simulations was prescribed as an input to the reforestation simulation, such that the effect of reforestation on land carbon storage was simulated in the absence of any additional CO_2 concentration feedback to the simulated land carbon changes.

The difference in global temperature change between the baseline and reforestation simulations reflects the net climate effect of reforestation in this model, accounting for both carbon storage and biophysical changes such as surface albedo that also result from vegetation cover changes. To further separate the effect of carbon storage and biophysical changes, we implemented a fourth simulation in which the CO_2 concentration from the reforestation scenario was used to drive a simulation that was otherwise equivalent to the baseline (no reforestation) scenario; this third simulation, therefore, captured the climate effect of enhanced land carbon storage in the absence of reforestation-induced surface albedo or other biophysical changes.

We note that in this set of simulations, we have not made any attempt to quantify or inform the discussion of what are feasible or optimal locations for reforestation to occur so as to avoid conflict with other land uses or with indigenous land rights[43]. We chose a forest regrowth pattern that reflects the reversal of historical deforestation in this model so as to quantify the climate consequences of such reforestation efforts, but not to argue that this pattern of reforestation has any particular rationale or merit.

Data availability

Model output data and analysis code used in this paper are available at https://doi.org/10.20383/102.0552[54].

Code availability

The model code for version 2.10 of the UVic ESCM is available on the official UVic ESCM webpage at http://terra.seos.uvic.ca/model/2.10. Custom model forcing files used here, as well as analysis code used to produce figures are available at the above data repository link.

Received: 3 November 2021; Accepted: 21 February 2022;

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Acknowledgements

The authors are grateful to Microsoft Corporation who provided funding to support the production of this manuscript, as well as the Natural Science and Engineering Research Council of Canada (Discovery Grants Program, RGPIN-2017-04159).

Author contributions

HDM, KZ, and AL developed the research questions and designed the study. AJM and SM performed the model simulations. C-MN and MD analyzed the model output and produced figures for the manuscript. HDM led the writing of the manuscript in consultation with all authors, who also provided editorial feedback through the writing process.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-022-00391-z.

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Peer review information *Communications Earth & Environment* thanks Remi Cardinael and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editor: Heike Langenberg. Peer reviewer reports are available.