Temporary Nature-based Carbon Removal Can Lower Peak Warming in a Well-below 2°C Scenario

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

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Abstract

There is growing recognition that meeting the climate objectives of the Paris Agreement will require the world to achieve net-zero carbon dioxide emissions around or before mid-century[1–4]. Natural climate solutions (NCS), which aim to preserve and enhance carbon storage in terrestrial or aquatic ecosystems[5,6], are increasingly being evoked as a potential contributor to net-zero emissions targets[7,8]. However, there is a risk that any carbon that we succeed in storing in land-based systems could be subsequently lost back to the atmosphere as a result of either climate-related or human-caused disturbances such as wildfire or deforestation[9–12]. Here we quantify the climate effect of NCS in a scenario where land-based carbon storage is enhanced over the next several decades, and this stored carbon is 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 decreased to net-zero during the time that NCS-sequestered carbon remained stored. We also demonstrate the importance of non-CO_2 climate effects of NCS implementation; decreases in surface albedo that result from temporary reforestation, for example, have the potential to counter almost half of the climate effect of carbon sequestration. Our results suggest that there is some climate benefit associated with NCS, even if the carbon storage is temporary, but only if implemented as a complement (and not an alternative) to ambitious fossil fuel CO_2 emissions reductions.

Introduction

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]. Alongside these targets, there is increased attention on possible strategies to remove carbon dioxide from the atmosphere (so-called carbon dioxide removal or CDR)[13–15] 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, natural climate solutions (NCS)[5–7] encompass a range of strategies aimed at preserving and enhancing carbon storage in ecosystems and on agricultural lands. A key appeal of NCS is the potential to contribute to climate mitigation efforts, while also generating additional co-benefits for human well-being and biodiversity[16].

NCS 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)[5–7]. To contribute to climate mitigation efforts, NCS 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, NCS 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 NCS do not have additional climate effects that might counter the climate benefit of enhanced carbon sequestration[17]. 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 NCS 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[5]. This positioning of NCS-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[4,18]. 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[9,11,19,20]. Quantifying the near-term carbon sequestration potential of NCS (as done by Refs [5,8,21], for example) is therefore not sufficient to gauge the potential contribution of NCS to the long-term temperature goal of the Paris Agreement. Rather than assuming permanent storage via NCS, we should in fact assume that this carbon storage will be temporary and then ask: to what extent will temporary carbon sequestration via NCS 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 climate mitigation scenarios ranging in ambition from relatively weak (SSP2-4.5) to very strong (SSP1-1.9). We use an intermediate complexity global climate model[22] 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 modelling setup reflects a case where NCS 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.

Idealized temporary carbon removal

We implemented three idealized NCS scenarios based on estimates of the feasible potential of NCS-based carbon removal[5,23], in which we prescribed an increasing rate of removal beginning in 2020, and reaching a maximum removal rate at 2030 of 3.64[23] and 10.4[5] Gt CO_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 Gt CO_2 per year until the year 2050 before decreasing it to zero at 2056, leading to a cumulative removal of 316 Gt CO_2 (Figure 1a and 1d). In all three scenarios, this removed carbon was subsequently returned to the atmosphere after 2056 such that cumulative CO_2 emissions at the year 2100 were equivalent to the baseline SSP scenarios. 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 (Figure 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 physical 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 (Figure 1c). This represents a global temperature response of between 0.5 and 0.55 °C per 1000 Gt CO_2 removal, similar to that found in previous idealized carbon removal experiments using this model[24]. 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 (Figure 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 (Figure 1c). For both scenarios, the annual warming rate over the next three decades 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, returning to the level of the baseline SSP scenarios shortly after the year 2100.

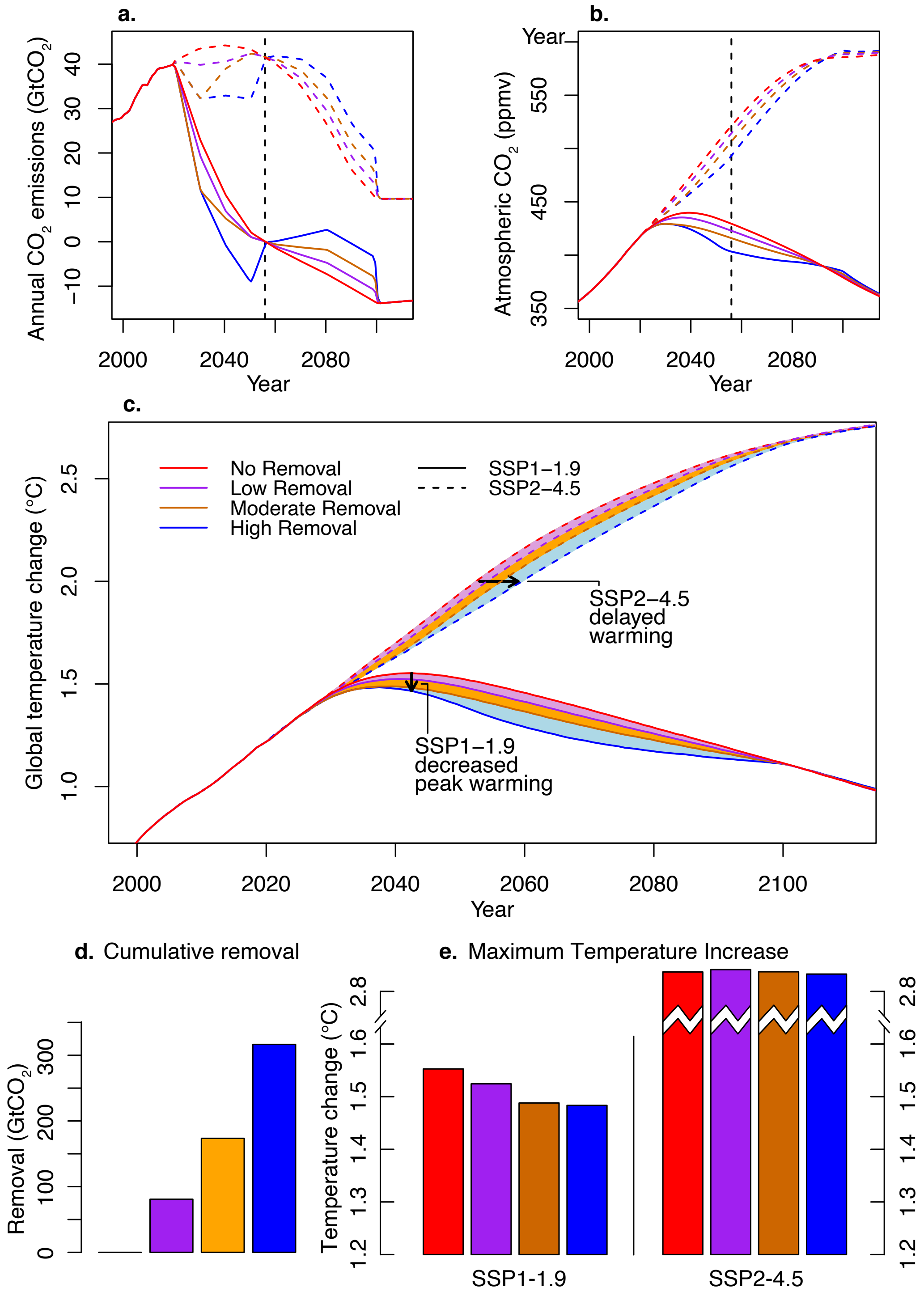

Figure 1: Climate response to prescribed temporary carbon removal scenarios. a and d: Prescribed CO$_2$ removal and subsequent return to the atmosphere resulted in cumulative temporary removals of 81 (purple lines/bars), 173 (orange lines/bars) and 316 (blue lines/bars) GtCO$_2$ relative to the baseline 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 and 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.

Reforestation-based temporary carbon removal

The simulations presented in Figure 1 show the potential climate response to a prescribed temporary carbon removal scenario, but do not represent any particular type of NCS, many of which would have additional climate effects beyond the removal of CO_2[8,17]. Most notable among potential secondary climate effects are potential surface albedo decreases that would result from changes in vegetation types associated with forest-based NCS such as afforestation and reforestation[5,8]. Here, we assessed the specific case of a temporary reforestation-based NCS scenario, in which we allowed forest distributions in the model to regrow to their historical (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). Modelled results therefore included both a temporary removal of atmospheric CO_2 and the associated changes in surface albedo resulting from simulated forest cover changes.

Our SSP1-1.9 forest regrowth scenario led to an increase of approximately 4 million km^2 of increased forested area in the 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 Figure 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. This increased land carbon storage resulted in a maximum atmospheric CO_2 drawdown of 12.3 ppm (Figure 2b) which represents 73% of the increased land carbon storage on account of decreased ocean carbon uptake in response to lower atmospheric CO_2 levels. This carbon removal effectiveness is not directly comparable with that calculated in the idealized scenarios shown in Figure 1 however, because the increased land carbon storage that we have calculated here includes a secondary response of global land vegetation to the lower CO_2 concentration induced by reforestation in our scenario; i.e. without this additional feedback, the land carbon increase in our simulations would have been higher than that indicated by the 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 surface albedo decreases caused by expanded forest cover (Figure 2c). The maximum 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 (Figure 2c). This represents a global temperature response to removal of 0.3 °C per 1000 $GtCO_2$ of removal. Compared to the idealized case in Figure 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 NCS strategies that do not affect land surface albedo. Indeed, when we removed the albedo effect from the reforestation simulation (dashed green lines on Figure 2; see Methods) the maximum temperature difference was 0.08°C (with a peak temperature decrease of 0.045°C) representing an equivalent global temperature effectiveness of removal as in the idealized removal simulations. This results emphasizes the potentially significant non-CO_2 effects of NCS implementation; our model does not represent all such potential effects however, most notably the effect of changing cloud cover in response to forest distribution changes[25]. 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 Figure 2c, rather than following either the blue or green lines.

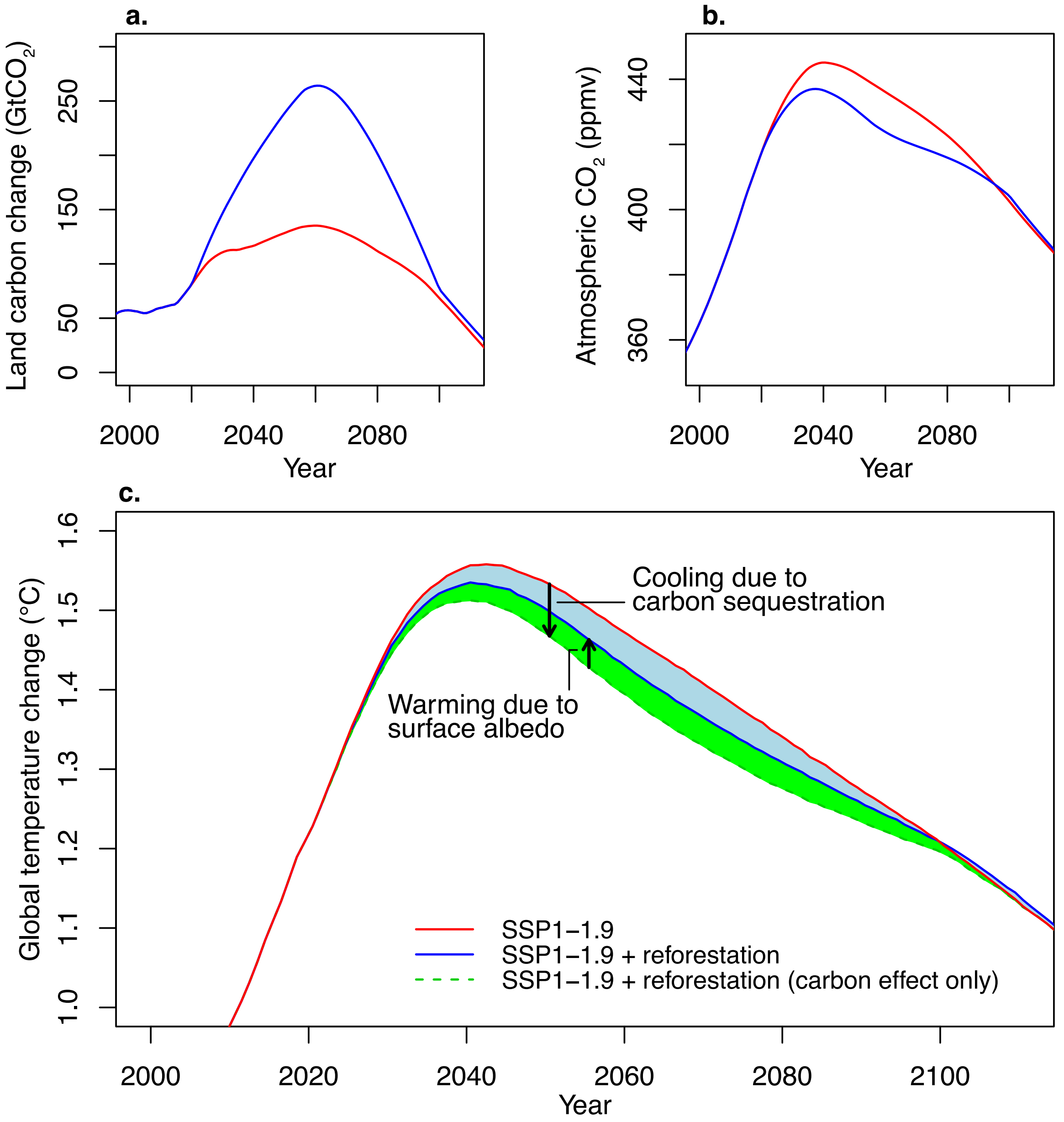

Figure 2: Climate response to a temporary reforestation-driven carbon removal scenario. a. Reforestation to year 1920 forest extent led to an additional 129 GtCO2 of land carbon storage relative to the baseline SSP1-1.9 scenario, which was subsequently returned to the atmosphere during the second half of this century. **b.** Atmospheric CO$_2$ concentrations decreased by 12.3 ppm in response to this increase 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. Land surface albedo decreases due to expanded global forest cover decreased this climate response by about 45% relative to the temperature change that would have occurred in the absence of albedo changes.

The magnitude of the surface albedo offset to reforestation-based carbon removal varied considerably 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 (Figure 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 sometimes exceeding 0.03 (3 percentage points) in areas of high reforestation. The climate consequence of this pattern of surface albedo decreases (Figure 3b) 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 (Figure 3c) occurred globally, with larger cooling at higher latitudes owing to positive feedbacks at high-latitude 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 (Figure 3d).

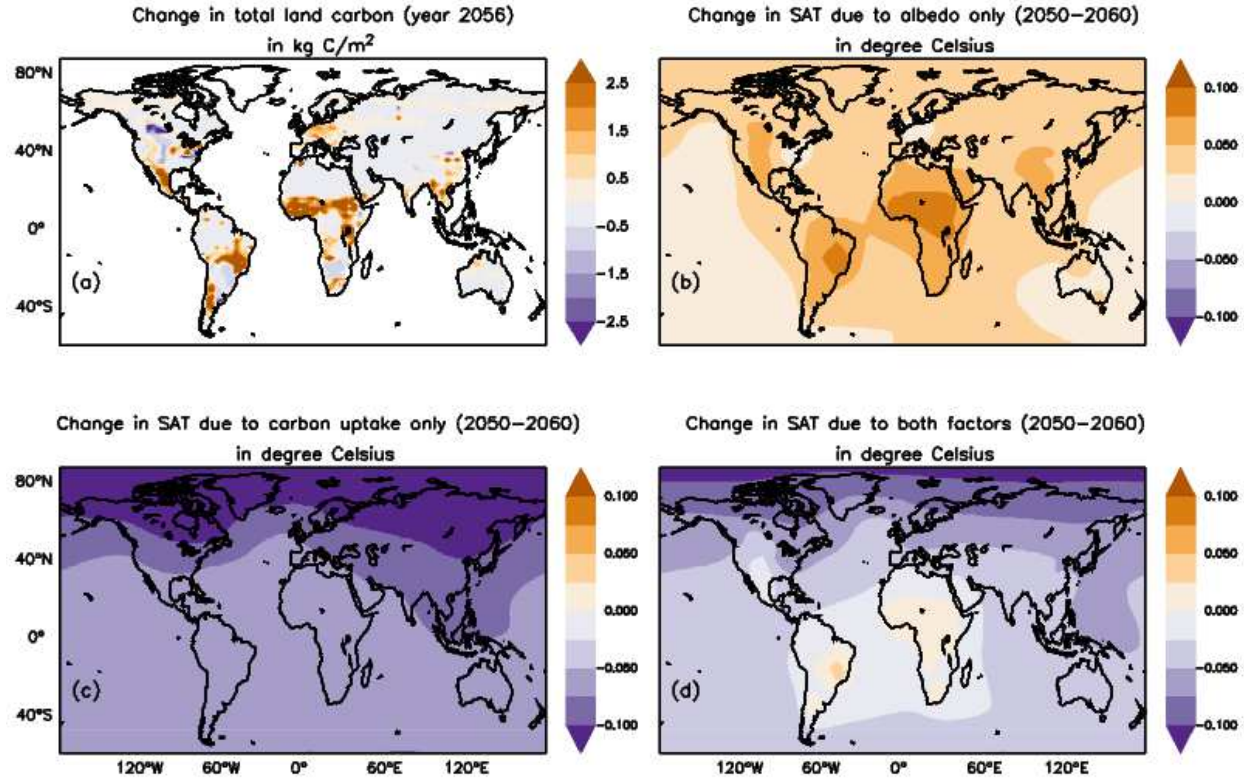

Figure 3: Spatial pattern of climate response to carbon sequestration and surface albedo changes resulting from temporary reforestation scenarios. a. Our scenario of reversed historical deforestation led to a global land carbon increase of 129 $GtCO_2$, which occurred primarily in tropical and subtropical regions. **b.** The associate 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. **d.** Consequently, the pattern of the net climate response to reforestation showed cooling over most of land areas, but a small net warming over some tropical continental regions.

The role of NCS in climate mitigation

Our results show that successful carbon sequestration via NCS 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 NCS-stored carbon remains sequestered in nature. This implies that realizing a tangible climate benefit from NCS will require net-zero fossil fuel CO_2 emissions to be achieved on the same timescale as the successful implementation of NCS. In the absence of this level of stringency in future mitigation effort, temporary NCS-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 NCS. Here, we quantified the effect of albedo changes associated with global reforestation efforts, and can conclude that NCS methods that modify surface albedo will have a reduced climate benefit. Previous discussions of NCS options have highlighted tropical forest reforestation as a more robust climate strategy compared to high-latitude reforestation for exactly this reason[5,21,26,27]; our results suggest that even tropical forest restoration has as 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 be a significant determinant of the net climate response to both tropical and mid-latitude forest cover changes[25]. Reviews of NCS options have also highlighted wetland restoration and soil carbon sequestration as “no-regrets” options with few negative consequences[16]. We caution, however, that wetland restoration would also change surface albedo, as well as the balance of carbon vs. methane emissions from the landscape. Similarly, soil carbon sequestration could also lead to altered surface albedo, particularly if achieved via the addition of biochar[28,29]. Following from our analysis, there is a need to quantify the full Earth-system response to both reforestation and a broader range of other NCS 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 NCS in climate mitigation. Recent claims of the carbon storage potential of NCS[5,6,8,21,30] have generally positioned NCS 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[31,32], 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 NCS 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 NCS efforts as interchangeable with fossil fuel emissions reductions. Rather, our finding that NCS could decrease peak warming requires that NCS be implemented independently alongside a rapid transition to net-zero fossil fuel CO_2 emissions, such that peak warming occurs before climate- or human-induced disturbances cause NCS-sequestered carbon to be lost back to the atmosphere.

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[5,33,34]. 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[35]. 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[34–36]. 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 stringent fossil fuel emission reductions.

Methods

We used the University of Victoria Earth System Climate Model[22,37] (UVic ESCM), an intermediate-complexity global climate model which includes dynamic spatial vegetation changes and an interactive land and ocean carbon cycle. 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. This model has been used and validated extensively over the past decade to look at research questions such as assessing the effect of historical land-use change on climate, assessing 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[18,38,39].

Using the UVic ESCM, we simulated the temporary storage of carbon via natural climate solutions (NCS) alongside two baseline climate mitigation scenarios: (1) SSP2-4.5, representing 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; and (2) SSP1-1.9, representing an ambitious mitigation scenario with peak 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. 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). This stored carbon was then returned to the atmosphere between 2056 and 2100 such that at the year 2100, the cumulative CO_2 emissions across scenarios with and without natural carbon removal was equal.

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 modelled land carbon pool, or of the land surface characteristics that would be associated with the implementation of particular types of NCS. The second case reflects a reforestation-based NCS scenario, in which carbon is sequestered by the land carbon pool, and both vegetation distributions and the associated land-surface characteristics in the model change in associated with this additional carbon storage.

(1) Idealized carbon dioxide removal scenarios

For the first set of idealized carbon dioxide removal scenarios, we implemented carbon removal due to NCS by adjusting prescribed fossil fuel + land-use CO_2 emissions to reflect the potential of nature-based carbon removal assessed by Refs [23] and [5]. Prescribed CO_2 emissions were decreased relative to the baseline scenario beginning in 2020, reaching a maximum difference of 3.64[23] or 10.4[5] $GtCO_2$ 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 Ref [5,33,34]), 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 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, after which land-use emissions were prescribed according to the carbon removal scenarios described above.

(2) Carbon removal via partial reforestation of agricultural areas

For the second set of simulations, we used prescribed changes in agricultural areas 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[22]. 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 at the year 2020, we implemented a global reforestation scenario, in which global 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.

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 surface albedo changes resulting from vegetation cover changes. To separate the effect of carbon storage and surface albedo changes, we implemented a third 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 changes.

We note that in this set of simulations, we do not make 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[35]. 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.

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