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# A comparison of the climate and carbon cycle effects of carbon removal by Afforestation and an equivalent reduction in Fossil fuel emissions

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**Abstract**

Afforestation and reduction of fossil fuel emissions are two major components of climate mitigation policies. However, their effects on the earth's climate are different because reduction of fossil fuel emissions directly alters the biogeochemical cycle of the climate system, while afforestation causes biophysical changes in addition to changes in the biogeochemical cycle. In this paper, we compare the climate and carbon cycle consequences of carbon removal by afforestation and an equivalent fossil fuel emission reduction using simulations from an intermediate complexity Earth system model. Our simulations show that the climate is cooler by 0.36°C, 0.47°C, and 0.42°C in the long term (2471-2500) in the case of reduced fossil fuel emissions compared to the case with afforestation when the emissions follow the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively. Though afforestation results in a lower atmospheric $CO_2$, the cooling from the reduced atmospheric $CO_2$ is partly offset by the warming from surface albedo decrease associated with the regrowth of forests. Since this warming effect from surface albedo decrease is nearly absent in the reduced fossil fuel emission case, the climate is relatively cooler, even though the atmospheric $CO_2$ levels are similar to the afforestation case. Thus, in terms of climate benefits, reducing fossil fuel emissions is relatively more beneficial than afforestation for the same amount of carbon removed from the atmosphere. Nevertheless, fossil fuel emission reduction and afforestation efforts should be pursued simultaneously as both lead to a decrease in global mean warming and reduced ocean acidification.

## 1 Introduction

Human activities in the industrial era have led to an increase in the concentration of greenhouse gases (GHGs) and an increase in global mean surface temperature (Masson-Delmotte et al., 2021). GHGs emitted by human activities include carbon dioxide, methane, nitrous oxide, etc., among which $CO_2$ is the most important GHG because of its long lifetime in the atmosphere (Archer et al., 2009; Montenegro et al., 2007; Archer, 2005; Archer and Brovkin, 2008; Moore and Braswell, 1994; Eby et al., 2009). The atmospheric $CO_2$ concentration has increased from approximately 277 ppm to 415ppm during the period 1750-2021 (Joos and Spahni, 2008; Keeling et al., 1976). Most of the anthropogenic emissions of atmospheric $CO_2$ result from either fossil fuel use or land use and land cover changes. In the recent decade (during the period 2010-19), the $CO_2$ emissions from fossil fuel use and land use and land cover changes are 9.6±0.5 PgC $yr^{-1}$ and 1.6 ± 0.7 PgC $yr^{-1}$, respectively (Friedlingstein et al., 2020).

Approximately 50% of the emitted carbon stays in the atmosphere while the rest is taken up by the land and ocean on decadal timescales (Friedlingstein et al., 2020). As a result of the increasing atmospheric $CO_2$, the global mean surface temperature has increased by 1.07°C from 1850-1900 to 2010-2019 (Masson-Delmotte et al., 2021). Global warming has been directly linked to an increase in the frequency of floods, extreme rainfall events, and forest fires in different parts of the world (Alfieri et al., 2015; Ali et al., 2019; Allan and Soden, 2008; Papalexiou and Montanari, 2019; Anderson et al., 2011; Canadell et al., 2021). Two major strategies are considered for mitigating climate change: i) reforestation/afforestation and ii) reduction of fossil fuel emissions. While both these methods reduce the carbon accumulation in the atmosphere, the net effect of these two actions on Earth's climate could be different. It may be noted that reforestation/afforestation is one of several carbon dioxide removal (CDR) options that have been suggested to mitigate climate change (Pacala and Socolow, 2004; Psarras et al., 2017; van Kooten, 2020).

The nature of the source or sink of atmospheric $CO_2$ could play a key role in determining its net effect on the earth's climate. For example, Jayakrishnan *et al.*, 2022 investigated the contrasting response of the climate system to emissions from fossil fuel use and deforestation and showed that these two emissions are fundamentally different in how they affect the climate system. However, adequate emphasis is not given to the nature of the source or sink in many contexts. An example for the implications of neglecting the non-radiative effects of the source of atmospheric $CO_2$ is described by Simmons & Matthews, 2016, where they show the importance of accounting for the biophysical changes due to land cover changes for calculating the transient climate response to cumulative carbon emissions (TCRE; a metric that defines the response of the global surface temperature to cumulative carbon emissions). In the current study, we address another set of related questions where the nature of the source or sink is important: Are the climate and carbon cycle effects of carbon removal by afforestation or an equivalent reduction of fossil fuel emissions the same? Which of these two actions is more beneficial from a climate change mitigation point of view?

Previous studies on the biophysical effects of land cover change are relevant in answering these questions (Anderson et al., 2011; Huang et al., 2018; Wang et al., 2014). The changes in land cover such as deforestation/afforestation have biophysical effects on the earth's climate, which results from changes in surface albedo and moisture and heat fluxes at the surface. The land surface albedo depends on the vegetation type since each vegetation has different optical properties (Gao et al., 2005;Henderson-Sellers and Wilson, 1983; Houldcroft *et al.*,

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2009). Therefore, large-scale changes in the vegetation type can significantly affect the earth's climate by changing the surface albedo. The grasslands have a higher albedo than forests. Additionally, in mid-latitudes, the snow-albedo feedback increases the surface albedo further when forests are converted to grasslands (Bonan et al., 1992; Claussen et al., 2001; Thackeray & Fletcher, 2016). Therefore, deforestation in mid-and high latitudes has a cooling effect because of an increase in the surface albedo (Bala et al., 2007; Bathiany et al., 2010; Govindasamy et al., 2001). Deforestation in the tropical regions also results in a decrease in evaporation, causing a warming effect (Bathiany et al., 2010; Davin & de Noblet-Ducoudre, 2010; Lean & Rowntree, 1993). Therefore, the net effect of deforestation (afforestation) is determined by the balance of the biophysical effects and the biogeochemical warming (cooling) effect from emission (removal) of carbon into (from) the atmosphere. The biophysical effects of afforestation are often neglected even though it could be comparable to the biogeochemical cooling effect of afforestation (Chen *et al.*, 2012, Huang *et al.*, 2018 and Shen *et al.*, 2022).

In this study, we compare the climate and carbon cycle effects of afforestation and reduction of fossil fuel emissions by considering two idealized simulations. In the first case, emissions follow three SSP scenarios (SSP2-4.5, SSP3-7.0 and SSP5-8.5) (Meinshausen et al., 2020) , and some amount of carbon is removed by afforestation. In the second case, fossil fuel emissions are reduced by the same amount that is additionally stored on land by afforestation in each of the three SSP scenarios. Figure S1 gives a schematic representation of the two simulations. The final climate state of these two cases is compared to assess the difference in the climate and carbon cycle effects of afforestation and reduced fossil fuel emissions.

## 2 Model description and Methodology

### 2.1 Model

Our simulations use the University of Victoria Earth System Climate Model (UVic ESCM) version 2.9, which is an Earth system Model of Intermediate Complexity (EMIC). UVic ESCM includes a vertically integrated energy-moisture balance atmospheric model, a primitive equation ocean general circulation model with 19 vertical layers, and a dynamic-thermodynamic sea ice model (Weaver et al., 2010). The dynamic vegetation model of UVic ESCM is the Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) (Cox, 2001) model. The TRIFFID dynamic vegetation model is coupled to the Met Office Surface Exchange Scheme (MOSES), which is a single layer version of the MOSES scheme described in Cox *et al.*, 1999. TRIFFID, together with MOSES scheme, simulates the distribution of vegetation over land and calculates terrestrial carbon stocks and fluxes. The inorganic ocean carbon cycle is included in the UVic model following the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) protocol and a marine ecosystem model (Keller et al., 2012). The sediment processes are represented by an oxic-only model of sediment respiration (Eby et al., 2009). The large-scale present-day climate is represented quite well in the UVic model (Weaver *et al*.,2001, Skvortsov *et al.*, 2009, Eby *et al.*, 2009 and Cao and Jiang, 2017).

### 2.2 Simulations

First, we spin up the model with the land use data corresponding to the year 1750 (Chini *et al., 2014)* for 7500 years to a steady state with an atmospheric $CO_2$ concentration of 280.8 ppm (Figure S2a, Table S1). The last 30

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years of this preindustrial spin-up simulation (PI_1750) has a global mean surface air temperature (SAT) of 13.2°C (Figure S2b, Table S1). Further details of the spin-up simulation are given in SI (Supplementary Information) TEXT S1. A historical simulation (HIST_1750_2005) is performed from 1750 to 2005 starting from the end of PI_1750 by prescribing historical fossil fuel emissions (Hoesly et al., 2018), land cover change (Chini et al., 2014), and volcanic forcing (Crowley, 2000). In the UVic model, land cover change during the historical period is modeled by prescribing the fraction of agricultural land (cropland and pastureland) in each grid. The dynamic vegetation model has representation for five natural vegetation types (broad leaf tree, needle leaf tree, $C_3$ grass, $C_4$ grass, and shrub) and bare soil. The atmospheric $CO_2$ concentration and SAT averaged over the last 30 years (1986-2005) of HIST_1750_2005 are 349.1ppm and 13.5°C, respectively (Figure S3, Table S1). A comparison of our historical simulation with observations shows that the model underestimates the amount of warming in the historical period (SI TEXT S2, Figure S3). The evolution of key climate variables during the historical simulation is shown in Figure S4, and further details of the historical simulation are provided in SI TEXT S2.

Starting from the historical simulation, three simulations are performed from the year 2006 to 2500 (Table 1): i) prescribed fossil fuel emission simulation with fixed agricultural land (FIXED_AGR) corresponding to the year 2005, ii) prescribed fossil fuel emission simulation with afforestation starting from the year 2006 (AFFOREST), and iii) prescribed fossil fuel emission simulations with reduced emissions (REDUCED_FF) and fixed agricultural land corresponding to the year 2005.

In the FIXED_AGR and REDUCED_FF cases, the fraction of the agricultural land is kept constant at values corresponding to the year 2005. Note that the five natural vegetation types can compete outside the agricultural land, and thus, the land cover in the FIXED_AGR and REDUCED_FF cases can change dynamically depending on the climate conditions. In the AFFOREST experiment, vegetation is allowed to regrow over the agricultural land by abruptly setting the agricultural land fraction to zero everywhere, which leads to additional storage of carbon in the land and a reduction in the growth of atmospheric $CO_2$. The fossil fuel emissions in FIXED_AGR and AFFOREST cases follow three extended SSP scenarios (SSP2-4.5, SSP3-7.0 and SSP5-8.5; Meinshausen et al., 2020). The fossil fuel emissions peak in the year 2040, 2100 and 2100 in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios, respectively, and reduces to zero by the year 2250 in the three scenarios. In the REDUCED_FF case, the fossil fuel emissions are reduced from the corresponding SSP scenarios by the same amount of carbon additionally stored over land in the AFFOREST case.

The AFFOREST (REDUCED_FF) simulations differ from the FIXED_AGR simulations only by afforestation (reduced fossil fuel emissions) in the AFFOREST (REDUCED_FF) simulations. Thus, the net effect of afforestation (reduced fossil fuel emissions) on the climate system is estimated by comparing the climate state of AFFOREST (REDUCED_FF) case with the FIXED_AGR case. Thus, in our analyses in the following sections, FIXED_AGR case is used as the reference case.

We recognize that the term "afforestation" in the real world refers to the intentional human activity of planting of trees to increase forest cover. However, the increase in forest in our AFFOREST simulations is due to dynamical

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natural evolution of tree type vegetation with no human intervention. Nevertheless, we use the term "afforestation" to refer to the increase in tree cover in these simulations.

## 3 Results

### 3.1 Effects of afforestation on land carbon and land surface albedo

In this section, we analyze the effects of afforestation on land carbon and land surface albedo in our simulations. In the AFFOREST case, regrowth of forests in abandoned agricultural land results in an increase in tree fraction from approximately 0.2 to 0.4, while in the FIXED_AGR and REDUCED_FF cases, tree fraction remains nearly unchanged at around 0.2 (Figure S5) in the three SSP scenarios. The larger tree fraction (averaged over 2471-2500) in the AFFOREST case compared to the FIXED_AGR case has similar spatial distribution in the three SSP scenarios, while there is virtually no difference in tree fraction (averaged over 2471-2500) between REDUCED_FF and FIXED_AGR cases everywhere in the three SSP scenarios (Figure S6).

In our preindustrial spinup simulation, the land carbon stock is 1789 PgC (Averaged over the last 30 years of PI_1750) (Table S1). In the historical simulation, it stays nearly unchanged at the preindustrial value (Figure S7) as the land carbon averaged over the last 30 years (1986-2005) of HIST_1750_2005 is 1779 PgC (Table S1). In the UVic model, the atmosphere to land carbon flux is the difference between net primary productivity (NPP) and the sum of soil respiration and vegetation burning flux (VEGBURN). VEGBURN is estimated as the carbon that is released into the atmosphere either from the removal of natural vegetation for expansion of agricultural land or from the removal of trees and shrubs that regrow on the prescribed agricultural land fraction. A brief description of VEGBURN is provided in SI TEXT S3. Because agricultural land fraction is zero everywhere in the AFFOREST case, VEGBURN is zero in the AFFOREST case (Figure S8). In the FIXED_AGR, AFFOREST, and REDUCED_FF simulations, NPP increases initially until around the year when emissions peak (2040 in SSP2-4.5 and 2100 in SSP3-7.0 and SSP5-8.5) due to $CO_2$ fertilization effect (Lobell and Field, 2008, Cernusak *et al.*, 2019 and Haverd *et al.*, 2020) in which elevated atmospheric $CO_2$ levels lead to increased plant productivity (Figure S9). The increase in atmosphere to land carbon flux due to this increase in NPP is partly offset by an increase in soil respiration (Figure S10) due to an increase in SAT.

The land carbon stock initially increases in all nine simulations until near the end of the 21$^{st}$ century (Figure S7) because the increase in NPP is larger than the increase in the sum of soil respiration and VEGBURN during this period. After the 21$^{st}$ century, emissions decrease, causing NPP to become relatively constant (Figure S9). Since soil respiration is larger in the SSP3-7.0 and SSP5-8.5 scenarios due to larger warming (Sect. 3.2), land carbon stock decreases after the emissions peak in the FIXED_AGR and REDUCED_FF simulations of the SSP3-7.0 scenario and in all three simulations of SSP5-8.5 scenario (Figure S7). In other simulations, land carbon stock becomes almost constant by around 2100 (Figure S7). After the cessation of emissions by the year 2250 (Figure S11), NPP becomes relatively constant (Figure S9) because of the absence of the $CO_2$ fertilization effect in all nine simulations. Global SAT increases only slightly after the cessation of emissions (Sect. 3.2); hence soil respiration also becomes almost constant near the end of all our simulations (Figure S10). Since NPP, soil respiration, and VEGBURN become

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relatively constant after the cessation of emissions (Figure S8, S9, and S10), the land carbon also becomes relatively constant after the cessation of emissions in all nine simulations (Figure S7).

The AFFOREST simulations show a larger increase in land carbon because of the forest regrowth, while the REDUCED_FF simulations show a similar land carbon as that of the FIXED_AGR simulations in the three SSP scenarios (Figure 1). In the AFFOREST simulations, the amount of carbon additionally stored over land (between 2006-2500) are 319.84 PgC, 418.93 PgC, and 379.21PgC in the SSP2-4.5, SSP3-7.0, and SSP 5-8.5 scenarios, respectively (Figure 1, Table S2). In the SSP 5-8.5 and SSP3-7.0 scenarios, the additional carbon stored in land is larger than that of the SSP 2-4.5 scenario (Figure 1), because of the larger $CO_2$ fertilization effect due to larger atmospheric $CO_2$ concentrations. However, added storage of land carbon is more in the SSP3-7.0 scenario than the SSP5-8.5 scenario which has a larger $CO_2$ concentration. This is because the larger temperature in the SSP5-8.5 scenario causes a larger increase in soil respiration than the increase in net primary productivity (NPP) due to $CO_2$ fertilization (Figure S12). In the AFFOREST simulations, land carbon (averaged over 2471-2500) is larger in regions with forest regrowth (Figure S13 and S6), while the spatial distribution of land carbon in the REDUCED_FF case is similar to the FIXED_AGR case in the three SSP scenarios (Figure S13). In the REDUCED_FF case fossil fuel emissions in corresponding SSP scenarios are reduced by the amount of carbon additionally stored over land in the AFFOREST simulations each year (Figure S14).

In addition to the increased land carbon, afforestation can significantly change the land surface albedo. The land surface albedo in our preindustrial simulation (PI_1750) is 0.28 (Table S1), which remains nearly unchanged in the historical simulation (HIST_1750_2005) (Figure S15, Table S1). In the FIXED_AGR, AFFOREST, and REDUCED_FF simulations, land surface albedo decreases initially and becomes nearly constant after 2250 in the three SSP scenarios (Figure S15). The land surface albedo is less in the AFFOREST case than in the FIXED_AGR case by 0.011 in the three SSP scenarios (Figure 2, Table S2), while the changes in land surface albedo in the REDUCED_FF case relative to the FIXED_AGR case is nearly zero in the three SSP scenarios (Figure 2, Table S2). The land surface albedo (averaged over 2471-2500) is lower in the AFFOREST case compared to FIXED_AGR in regions with forest regrowth (Figure S16 and S6), while in the REDUCED_FF case, the land surface albedo (averaged over the last 30 years) is similar to the FIXED_AGR case everywhere in the three SSP scenarios (Figure S16).

In summary, we find that afforestation leads to additional carbon storage over land and lower land surface albedo in the AFFOREST case compared to the FIXED_AGR and REDUCED_FF cases where agricultural land fraction is maintained at year 2005 values.

### 3.2 Evolution of Atmospheric $CO_2$ and Surface Air Temperature

The atmospheric $CO_2$ concentration and SAT in our preindustrial simulation (PI_1750) are 280.8ppm and 13.2 °C (averaged over the last 30 years of PI_1750) (Figure S2, Table S1), respectively. In our historical simulation (HIST_1750_2005), atmospheric $CO_2$ increases due to fossil fuel and land use change emissions. At the end of the historical simulation, atmospheric $CO_2$ concentration increases to 349.1ppm (averaged over 1976-2005) (Figure S3, Table S1), and consequently, SAT increases to 13.5°C (Figure S3, Table S1).

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The increase in atmospheric $CO_2$ (averaged over 2471-2500) in our nine simulations compared to HIST_1750 (averaged over 1976-2005) vary from 140ppm to 1675ppm (Figure S17, Table S3). Initially, atmospheric $CO_2$ increases until around the cessation of fossil fuel emissions in the year 2250 in all simulations because fossil fuel emissions add more carbon to the atmosphere. After the cessation of emissions around 2250, atmospheric $CO_2$ decreases slightly until the end of the simulations because of further carbon uptake by the ocean (Sect. 3.3) in all nine simulations. The atmospheric $CO_2$ concentration is similar and smaller in the AFFOREST and REDUCED_FF simulations compared to the FIXED_AGR in the three SSP scenarios because of the removal of carbon by afforestation and reduced fossil fuel emissions, respectively (Figure S17). The decrease in atmospheric $CO_2$ because of afforestation or reduction of fossil fuels is almost twice in the SSP3-7.0 and SSP5-8.5 scenarios compared to SSP2-4.5 (Figure 3, Table S3). This is due to two reasons: i) the amount of carbon removed by land is larger in the SSP3-7.0 and SSP5-8.5 scenarios because of the larger $CO_2$-fertilization effect as discussed in Sect. 3.1 ii)) larger ocean carbon uptake in the FIXED_AGR case relative to AFFOREST case in the SSP3-7.0 and SSP5-8.5 scenarios compared to SSP2-4.5 (Table S2).

The future projections of changes in SAT (averaged over 2471-2500) in our nine simulations relative to HIST_1750 (averaged over 1976-2005) vary from 2°C to 8°C (Figure S18, Table S3). In the three SSP scenarios, the REDUCED_FF case simulates a smaller SAT increase compared to the AFFOREST and FIXED_AGR cases (Figure S18). The afforestation in the AFFOREST case results in a cooling of 0.31°C and 0.1°C and a warming of 0.05°C in the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenario, respectively, while the reduction of fossil fuel emissions in the REDUCED_FF case results in a cooling of 0.66°C, 0.56°C and 0.36°C in the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenario, respectively when compared to the FIXED_AGR case (Figure 4, Table S3).

In the AFFOREST case, the cooling effect of $CO_2$ removal from the afforestation is partly offset by the warming effect of the changes in surface albedo because of the growth of forests. Hence, the AFFOREST case has a larger SAT than the REDUCED_FF case in the three SSP scenarios (Figure 4 and S18). In the SSP3-7.0 and SSP5-8.5 scenarios, this offsetting is almost full so that the AFFOREST and FIXED_AGR cases have similar SAT (Figure 4 and S18). However, in the SSP2-4.5 scenario, though the reduction in atmospheric $CO_2$ is smaller (Figure 4 and S18), the cooling effect of $CO_2$ removal is larger as temperature change scales with the logarithm of atmospheric $CO_2$ levels. Therefore, in the SSP2-4.5 scenario, the warming effect of the regrowth of forests does not completely offset the cooling effect of removing atmospheric $CO_2$.

The spatial patterns of SAT (averaged over 2471-2500) in the AFFOREST and REDUCED_FF cases are compared with the FIXED_AGR case in Figure 5. The REDUCED_FF case is cooler in all regions with respect to the FIXED_AGR case in the three SSP scenarios (Figure 5), while AFFOREST case shows regional warming in the SSP3-7.0 and SSP5-8.5 scenarios. This regional warming in the AFFOREST case is more prominent over land, where the afforestation results in a lower land surface albedo (Figure 5 and S16).

In summary, we find that a reduction in fossil fuel emissions is more effective than afforestation since the cooling benefits of storing atmospheric carbon in vegetation is partly offset by the decrease in the albedo of the surface

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in the AFFOREST case. However, afforestation is beneficial for reducing ocean acidification, as shown in the next section.

### 3.3 Ocean carbon content and Surface Ocean pH

The ocean carbon content in the PI_1750 simulation (averaged over 2471-2500) is 37287 PgC (Table S1). In our historical simulation (HIST_1750_2005), ocean carbon content increases as increasing $CO_2$ levels in the atmosphere results in an increased carbon uptake by the ocean (Figure S19). The increase in ocean carbon content averaged over the period 1976-2005 of HIST_1750_2005 is 82 PgC (Table S1), The cumulative carbon uptake during the historical period is 113PgC, which falls in the observed range of 105±20PgC (Masson-Delmotte et al., 2021).

The ocean carbon content increases in the FIXED_AGR, AFFOREST and REDUCED_FF simulations in the three SSP scenarios. The FIXED_AGR case shows the largest amount of ocean carbon content in the three SSP scenarios (Figure S19), because of larger atmospheric $CO_2$ in the FIXED_AGR case compared to AFFOREST and REDUCED_FF cases. The spatial pattern of the ocean carbon content (averaged over 2471-2500) in AFFOREST and REDUCED_FF cases relative to the FIXED_AGR case shows that the ocean carbon content increase is less in the AFFOREST and REDUCED_FF cases compared to FIXED_AGR case in all regions in the three SSP scenarios (Figure S20). In the high emissions scenarios (SSP3-7.0 and SSP5-8.5), the reduction in the ocean carbon content in the AFFOREST and REDUCED_FF cases are less compared to SSP2-4.5 (Figure 6 and S19) because of the buffering effect (Middelburg et al., 2020). The reduction of ocean carbon content (averaged over 2471-2500) in the AFFOREST and REDUCED_FF cases compared to the FIXED_AGR case is more pronounced in the surface ocean as the surface ocean adjusts more rapidly to the changes in atmospheric $CO_2$ (Figure S21). A longer simulation would be required for larger changes in carbon content in the deep ocean.

The surface ocean pH in our preindustrial state is 8.15 (averaged over the last 30 years of PI_1750). By year 2005, the surface ocean pH (averaged over 1976-2005) reduces to 8.09 as the ocean takes up more carbon as atmospheric $CO_2$ increases during the historical period (Figure S22). In the FIXED_AGR, AFFOREST and REDUCED_FF simulations, surface ocean pH decreases until the fossil fuel emissions reduce to zero in the year 2250 and increases slightly after the emissions cease (Figure 22). The AFFOREST and REDUCED_FF cases show larger and similar changes in surface ocean pH in comparison with the FIXED_AGR case in the three SSP scenarios (Figure 7) because of smaller increase in ocean carbon content in the AFFOREST and REDUCED_FF cases (Figure 6 and S19, and Table S3).

The AFFOREST and REDUCED_FF cases show larger surface ocean pH (averaged over 2471-2500) in all regions in the three SSP scenarios relative to the corresponding FIXED_AGR cases, because of smaller ocean carbon content as a result of reduced atmospheric $CO_2$ (Figure 8). In the high emissions scenarios (SSP3-7.0 and SSP5-8.5), the increase in surface ocean pH in the AFFOREST and REDUCED_FF cases are less compared to SSP2-4.5 (Figure 7 and Figure 8) because the reduction in ocean carbon is smaller in higher emissions scenarios (Figure 6).

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As discussed in the previous section, the cooling effect of afforestation is offset by the warming effect of surface albedo changes. However, as shown in this section, afforestation is useful to reduce the effects of increased ocean carbon content and thereby ocean acidification.

**4. Conclusions**

Afforestation and reduced fossil fuel emissions are two major components of climate change mitigation currently adopted to slow climate change. Understanding the net effects of afforestation and reduced fossil fuel emissions is important for the development of climate mitigation strategies. In this paper, we have shown that the climate response to carbon removal by afforestation and an equivalent reduction in fossil fuel emissions is different because of the biophysical effects of afforestation, which is often neglected in the development of climate mitigation strategies.

We have analyzed the relative effectiveness of afforestation and reduction of fossil fuel emissions for mitigating climate change using climate model simulations. Our results show that allowing the forests to grow back by abandoning all the agricultural land in the year 2005 leads to an additional storage of carbon over land of 319.84 PgC, 418.93 PgC, and 379.21PgC by 2500 (averaged over 2471-2500) in the SSP 2-4.5, SSP 3-7.0 and SSP5-8.5 scenarios, respectively. If fossil fuel emissions are reduced by the same amount of carbon that is additionally stored over land, the climate is cooler in the reduced fossil fuel emission case compared to the afforestation case. The relative cooling is 0.36°C, 0.47°C and 0.42°C in the reduced fossil fuel emission case compared to the afforestation case in the year 2500 (averaged over 2471-2500) in the SSP 2-4.5, SSP 3-7.0 and SSP 5-8.5 scenario, respectively. In the case of afforestation, the change in vegetation cover from grasslands to forests has a warming effect which nearly offsets the cooling effect from carbon removed from the atmosphere. In our simulations, the cooling effect of afforestation is completely offset by its warming effect in the higher emission scenarios (SSP 3-7.0 and SSP 5-8.5) and partially offset in lower emission scenario (SSP 2-4.5). This suggests that afforestation may have a larger climate benefit in the lower emission scenarios.

There are several limitations to our study. First, the afforestation in our model is highly idealized. In our afforestation simulations, we assume that the entire agricultural land in the year 2005 is abandoned and vegetation is allowed to regrow abruptly, while in the real-world implementing afforestation at this scale would take a longer period. Also, in our simulations, vegetation grows back naturally according to the climate conditions over the abandoned agricultural land, while in the real world, it might be possible to grow trees artificially in areas where the climate conditions do not support the growth of trees. Second, many processes in the model are highly simplified representations aimed at achieving a lower computational cost. For example, the dynamic vegetation model in our simulation has only five plant functional types, while the real-world ecosystems are far more diverse and complex. However, the simplified representation enables us to understand the role of climate-vegetation feedbacks in longer time scales with less computational cost. Even though the afforestation representation in our model is highly idealized and there are uncertainties in the processes that are represented in the model, we believe that the qualitative conclusions would not be affected by these limitations.

Based on our results, we conclude that a reduction in fossil fuel emissions is more effective than afforestation in mitigating climate change. Though afforestation is relatively less effective in mitigating climate change, it has other benefits such as reducing ocean acidification: the removal of carbon from the atmosphere results in slightly reduced carbon in the ocean, which leads to higher surface ocean pH and less ocean acidification. Therefore, a better strategy to address climate change is to reduce fossil fuel emission as well as pursue afforestation efforts.

**Data availability**

All data that support the findings of the study will be made available at the Zenodo database. DOI: 10.5281/zenodo.7321684.

**Author Contribution**

Govindasamy Bala formulated the idea behind the study. Govindasamy Bala and K U Jayakrishnan designed the experiments. K U Jayakrishnan performed the experiments. Govindasamy Bala and K U Jayakrishnan contributed to the writing and editing of the manuscript.

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**Competing Interest Statement**

The authors do not have any competing interests to disclose

**References**

Alfieri, L., Burek, P., Feyen, L., and Forzieri, G.: Global warming increases the frequency of river floods in Europe, Hydrol. Earth Syst. Sci., 19, 2247–2260, https://doi.org/10.5194/HESS-19-2247-2015, 2015.

Ali, H., Modi, P., and Mishra, V.: Increased flood risk in Indian sub-continent under the warming climate, Weather Clim. Extrem., 25, 100212, https://doi.org/10.1016/J.WACE.2019.100212, 2019.

Allan, R. P. and Soden, B. J.: Atmospheric warming and the amplification of precipitation extremes, Science (80-. )., 321, 1481–1484, https://doi.org/10.1126/SCIENCE.1160787/SUPPL_FILE/ALLAN.SOM.PDF, 2008.

Anderson, R. G., Canadell, J. G., Randerson, J. T., Jackson, R. B., Hungate, B. A., Baldocchi, D. D., Ban-Weiss, G. A., Bonan, G. B., Caldeira, K., Cao, L., Diffenbaugh, N. S., Gurney, K. R., Kueppers, L. M., Law, B. E., Luyssaert, S., and O'Halloran, T. L.: Biophysical considerations in forestry for climate protection, Front. Ecol. Environ., 9, 174–182, https://doi.org/10.1890/090179, 2011.

https://doi.org/10.5194/bg-2022-227
Preprint. Discussion started: 6 December 2022




Archer, D.: Fate of fossil fuel CO2 in geologic time, J. Geophys. Res. Ocean., 110, 1–6, https://doi.org/10.1029/2004JC002625, 2005.

Archer, D. and Brovkin, V.: The millennial atmospheric lifetime of anthropogenic CO2, Clim. Chang. 2008 903, 90, 283–297, https://doi.org/10.1007/S10584-008-9413-1, 2008.

Archer, D. U. of C. > D. of G. S., Eby, M. U. of V. > S. of E. and O. S., Brovkin, V. M. P. I. for M., Ridgwell, A. U. of B. > S. of G. S., Cao, L. C. I. > D. of G. E., Mikolajewicz, U. M. P. I. for M., Caldeira, K. C. I. > D. of G. E., Matsumoto, K. U. of M. > D. of G. and G., Munhoven, G. U. de L.-Ul. > D. d'astrophys. . géophysique et océanographie (AGO) > L. de physique atmosphérique et planétaire (LPAP), Montenegro, A. U. of V. > S. of E. and O. S., and Tokos, K. U. of M. > D. of G. and G.: Atmospheric Lifetime of Fossil Fuel Carbon Dioxide, Annu. Rev. Earth Planet. Sci., 37, 117–134, https://doi.org/10.1146/ANNUREV.EARTH.031208.100206, 2009.

Canadell, J. G., Meyer, C. P. (Mick., Cook, G. D., Dowdy, A., Briggs, P. R., Knauer, J., Pepler, A., and Haverd, V.: Multi-decadal increase of forest burned area in Australia is linked to climate change, Nat. Commun. 2021 121, 12, 1–11, https://doi.org/10.1038/s41467-021-27225-4, 2021.

Cao, L. and Jiang, J.: Simulated Effect of Carbon Cycle Feedback on Climate Response to Solar Geoengineering, Geophys. Res. Lett., 44, 12,484-12,491, https://doi.org/10.1002/2017GL076546, 2017.

Cernusak, L. A., Haverd, V., Brendel, O., Le Thiec, D., Guehl, J.-M., and Cuntz, M.: Robust response of terrestrial plants to rising CO2, Trends Plant Sci., 24, 578–586, 2019.

Chen, G. S., Notaro, M., Liu, Z., and Liu, Y.: Simulated Local and Remote Biophysical Effects of Afforestation over the Southeast United States in Boreal Summer, J. Clim., 25, 4511–4522, https://doi.org/10.1175/JCLI-D-11-00317.1, 2012.

Chini, L. P., Hurtt, G. C., and Frolking, S.: LUH1: Harmonized Global Land Use for Years 1500-2100, V1, ORNL DAAC, 2014.

Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R., and Smith, J.: The impact of new land surface physics on the GCM simulation of climate and climate sensitivity, Clim. Dyn. 1999 153, 15, 183–203, https://doi.org/10.1007/S003820050276, 1999.

Crowley, T. J.: Causes of climate change over the past 1000 years, Science (80-. )., 289, 270–277, https://doi.org/10.1126/SCIENCE.289.5477.270/ASSET/F912AC33-9AD4-4809-BCB0-D30391499765/ASSETS/GRAPHIC/SE2708679006.JPEG, 2000.

Eby, M., Zickfeld, K., Montenegro, A., Archer, D., Meissner, K. J., and Weaver, A. J.: Lifetime of Anthropogenic Climate Change: Millennial Time Scales of Potential CO2 and Surface Temperature Perturbations, J. Clim., 22, 2501–2511, https://doi.org/10.1175/2008JCLI2554.1, 2009.

Haverd, V., Smith, B., Canadell, J. G., Cuntz, M., Mikaloff-Fletcher, S., Farquhar, G., Woodgate, W., Briggs, P. R.,

https://doi.org/10.5194/bg-2022-227
Preprint. Discussion started: 6 December 2022



and Trudinger, C. M.: Higher than expected CO2 fertilization inferred from leaf to global observations, Glob. Chang. Biol., 26, 2390–2402, 2020.

Henderson-Sellers, A. and Wilson, M. F.: Surface albedo data for climatic modeling, Rev. Geophys., 21, 1743–1778, https://doi.org/10.1029/RG021I008P01743, 1983.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J. I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.: Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), Geosci. Model Dev., 11, 369–408, https://doi.org/10.5194/GMD-11-369-2018, 2018.

Houldcroft, C. J., Grey, W. M. F., Barnsley, M., Taylor, C. M., Los, S. O., and North, P. R. J.: New Vegetation Albedo Parameters and Global Fields of Soil Background Albedo Derived from MODIS for Use in a Climate Model, J. Hydrometeorol., 10, 183–198, https://doi.org/10.1175/2008JHM1021.1, 2009.

Huang, L., Zhai, J., Liu, J., and Sun, C.: The moderating or amplifying biophysical effects of afforestation on CO2-induced cooling depend on the local background climate regimes in China, Agric. For. Meteorol., 260–261, 193–203, https://doi.org/10.1016/J.AGRFORMET.2018.05.020, 2018.

Jayakrishnan, K. U., Bala, G., Cao, L., and Caldeira, K.: Contrasting climate and carbon-cycle consequences of fossil-fuel use versus deforestation disturbance, Environ. Res. Lett., 17, 064020, https://doi.org/10.1088/1748-9326/AC69FD, 2022.

Joos, F. and Spahni, R.: Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years, Proc. Natl. Acad. Sci. U. S. A., 105, 1425–1430, https://doi.org/10.1073/PNAS.0707386105, 2008.

Keeling, C. D., Bacastow, R. B., Bainbridge, A. E., Ekdahl Jr, C. A., Guenther, P. R., Waterman, L. S., and Chin, J. F. S.: Atmospheric carbon dioxide variations at Mauna Loa observatory, Hawaii, Tellus, 28, 538–551, 1976.

van Kooten, G. C.: How effective are forests in mitigating climate change?, For. Policy Econ., 120, 102295, 2020.

Lobell, D. B. and Field, C. B.: Estimation of the carbon dioxide (CO2) fertilization effect using growth rate anomalies of CO2 and crop yields since 1961, Glob. Chang. Biol., 14, 39–45, 2008.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., and Gomis, M. I.: Climate change 2021: the physical science basis, Contrib. Work. Gr. I to sixth Assess. Rep. Intergov. panel Clim. Chang., 2, 2021.

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., Smith, S. J., Van Den Berg, M., Velders, G. J. M., Vollmer, M. K., and Wang, R. H. J.: The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to

2500, Geosci. Model Dev., 13, 3571–3605, https://doi.org/10.5194/GMD-13-3571-2020, 2020.

Middelburg, J. J., Soetaert, K., and Hagens, M.: Ocean alkalinity, buffering and biogeochemical processes, Rev. Geophys., 58, e2019RG000681, 2020.

Montenegro, A., Brovkin, V., Eby, M., Archer, D., and Weaver, A. J.: Long term fate of anthropogenic carbon, Geophys. Res. Lett., 34, https://doi.org/10.1029/2007GL030905, 2007.

Moore, B. and Braswell, B. H.: The lifetime of excess atmospheric carbon dioxide, Global Biogeochem. Cycles, 8, 23–38, https://doi.org/10.1029/93GB03392, 1994.

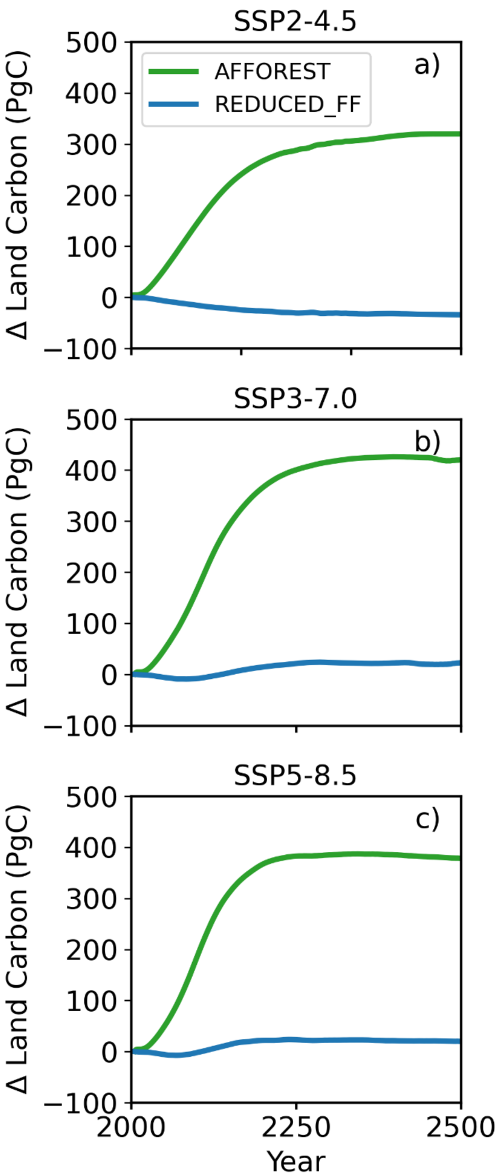
Pacala, S. and Socolow, R.: Stabilization wedges: solving the climate problem for the next 50 years with current technologies, Science (80-. )., 305, 968–972, 2004.

Papalexiou, S. M. and Montanari, A.: Global and Regional Increase of Precipitation Extremes Under Global Warming, Water Resour. Res., 55, 4901–4914, https://doi.org/10.1029/2018WR024067, 2019.

Psarras, P., Krutka, H., Fajardy, M., Zhang, Z., Liguori, S., Dowell, N. Mac, and Wilcox, J.: Slicing the pie: how big could carbon dioxide removal be?, Wiley Interdiscip. Rev. Energy Environ., 6, e253, 2017.

Shen, W., He, J., He, T., Hu, X., Tao, X., and Huang, C.: Biophysical Effects of Afforestation on Land Surface Temperature in Guangdong Province, Southern China, J. Geophys. Res. Biogeosciences, 127, e2022JG006913, https://doi.org/10.1029/2022JG006913, 2022.

https://doi.org/10.5194/bg-2022-227
Preprint. Discussion started: 6 December 2022


425 **Figure 1.** Changes in global total land carbon stock in the AFFOREST (green; ΔAFFOREST) and REDUCED_FF (blue; Δ REDUCED_FF) cases relative to the FIXED_AGR case in the a) SSP2-4.5 b) SSP3-7.0 and c) SSP5-8.5 scenarios. In the AFFOREST case, land carbon is larger than the FIXED_AGR case by 319.84 PgC, 418.93 PgC, and 379.21PgC in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios by year 2500 (averaged over 2471-2500) respectively, while the difference between land carbon in REDUCED_FF and FIXED_AGR is nearly zero in the three SSP scenarios.

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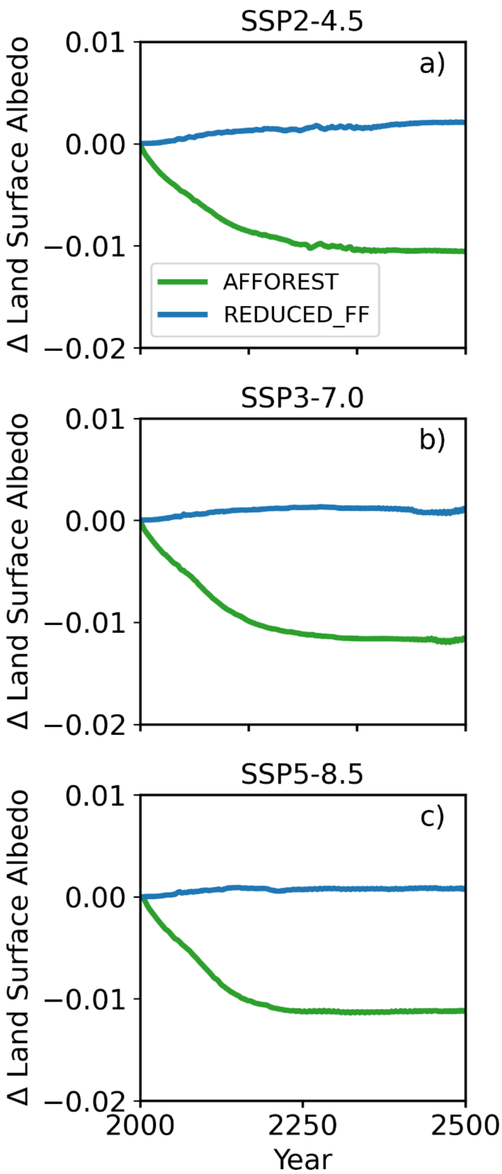


430 **Figure 2.** Changes in global mean land surface albedo in the AFFOREST (green; ΔAFFOREST) and REDUCED_FF (blue; Δ REDUCED_FF) cases relative to the FIXED_AGR case in the a) SSP2-4.5 b) SSP3-7.0 and c) SSP5-8.5 scenarios. In the AFFOREST case, land surface albedo is smaller by 0.011 (averaged over (2471-2500) in the three SSP scenarios, while the REDUCED_FF case has similar land surface albedo as in the FIXED_AGR case in the three SSP scenarios.

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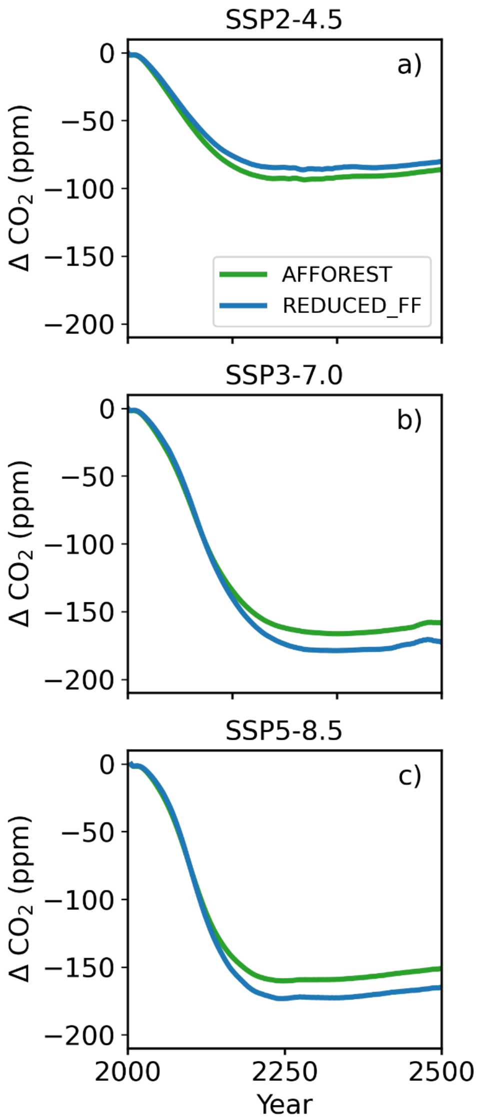


**Figure 3.** Changes in global mean atmospheric $CO_2$ concentration in the AFFOREST (green; ΔAFFOREST) and REDUCED_FF (blue; Δ REDUCED_FF) cases relative to the FIXED_AGR case in the a) SSP2-4.5 b) SSP3-7.0 and c) SSP5-8.5 scenarios. The decrease in atmospheric $CO_2$ because of afforestation or reduced fossil fuel emissions is almost twice in SSP3-7.0 and SSP5-8.5 compared to SSP2-4.5 due to two reasons: i) amount of carbon removed by land is larger in the SSP3-7.0 and SSP5-8.5 scenarios because of larger $CO_2$-fertilization effect as discussed in Sect 3.1 ii)) larger ocean carbon uptake in the FIXED_AGR case relative to the AFFOREST and REDUCED_FF cases in the SSP3-7.0 and SSP5-8.5 scenarios compared to SSP2-4.5 (Table S2).

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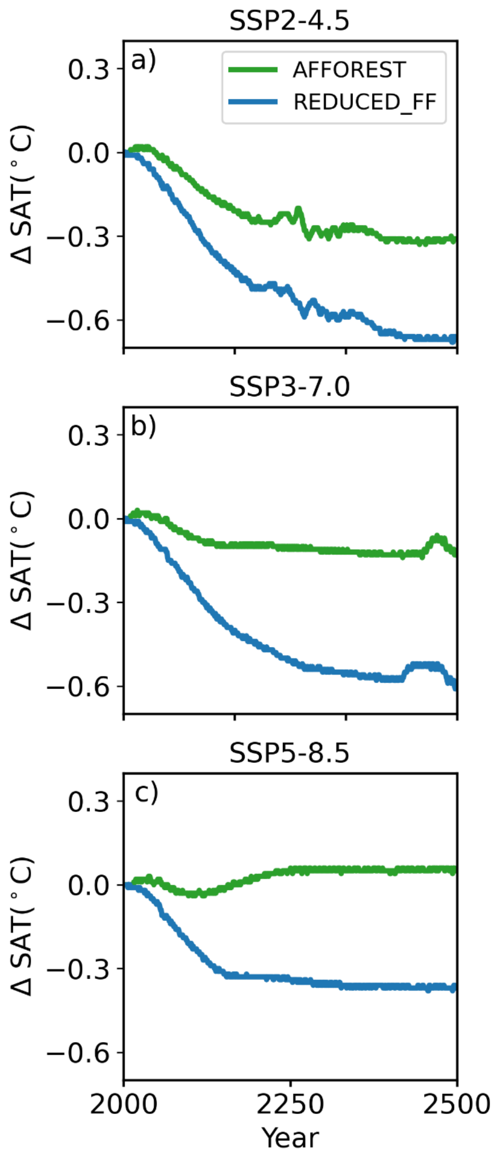


**Figure 4.** Changes in global mean surface air temperature in the AFFOREST (green; ΔAFFOREST) and REDUCED_FF (blue; Δ REDUCED_FF) cases relative to the FIXED_AGR case in the a) SSP2-4.5 b) SSP3-7.0 and c) SSP5-8.5 scenarios. The REDUCED_FF case has lower SAT than the FIXED_AGR case in the three SSP scenarios case because of reduced fossil fuel emissions in the REDUCED_FF case. In the AFFOREST case, the cooling effect of removal of $CO_2$ is nearly offset by the warming effect of regrowth of forests. Hence, the AFFOREST case has similar SAT as that of FIXED_AGR in the SSP3-7.0 and SSP5-8.5 scenarios. However, in the SSP2-4.5 scenario, though the reduction in atmospheric $CO_2$ is smaller (Figures 4 and S17), the cooling effect of removal is larger because global mean temperature change scales with the logarithm of atmospheric $CO_2$ levels. Therefore, in the SSP2-4.5 scenario, the warming effect of the regrowth of forests does not completely offset the cooling effect of removing atmospheric $CO_2$.

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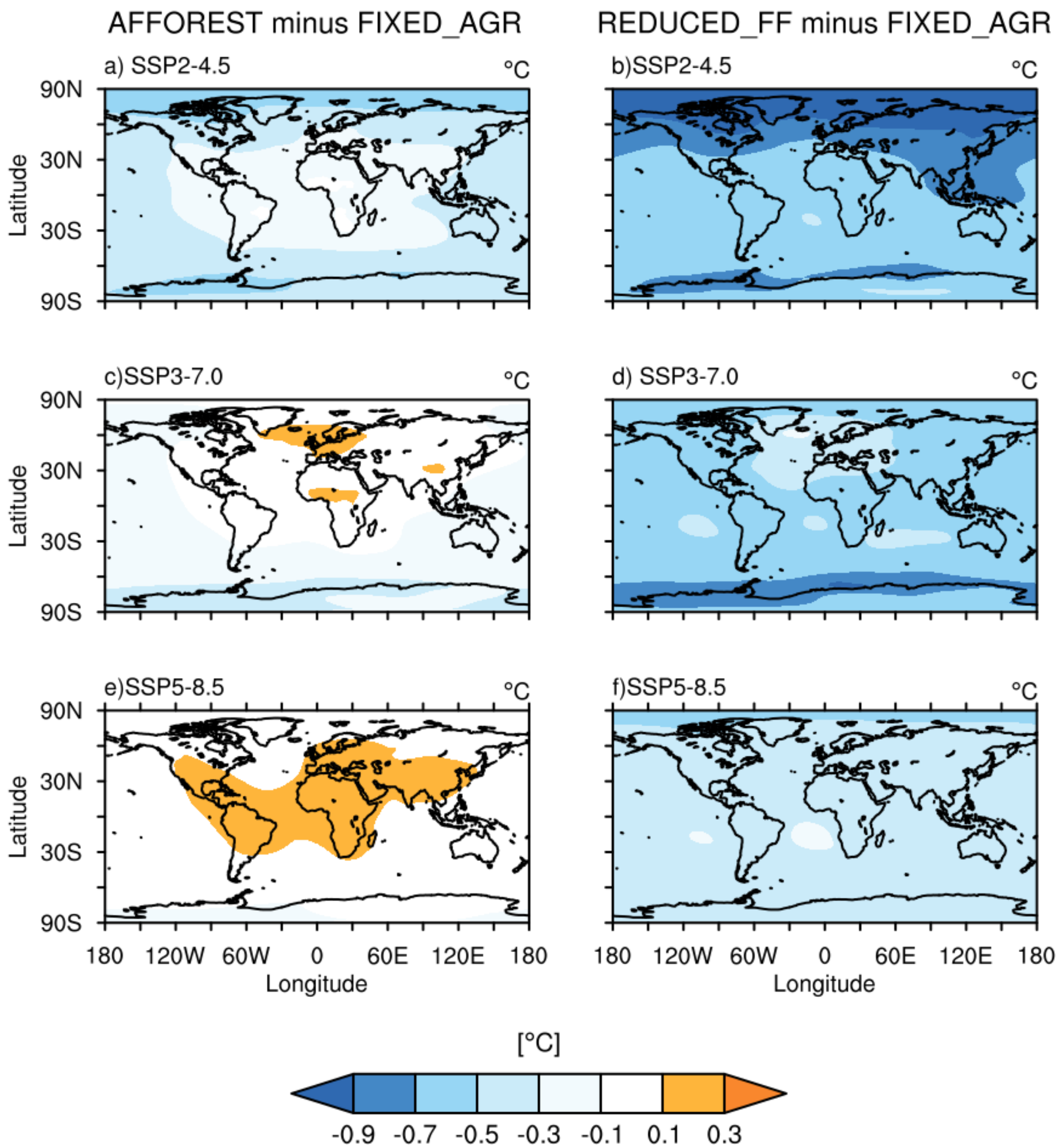


**Figure 5.** The left (right) panel shows the spatial pattern of the difference in global mean surface air temperature (SAT) averaged over the last 30 years between the AFFOREST (REDUCED_FF) and FIXED_AGR cases. The top, middle and bottom panels correspond to the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios, respectively. The REDUCED_FF case shows lower SAT everywhere relative to the FIXED_AGR case in the three SSP scenarios, while the AFFOREST case shows regional warming in the SSP3-7.0 and SSP5-8.5 scenarios. Note that the regions of warming in the AFFOREST case is more prominent over land where the forest regrowth results in a lower land surface albedo (Figure S15).

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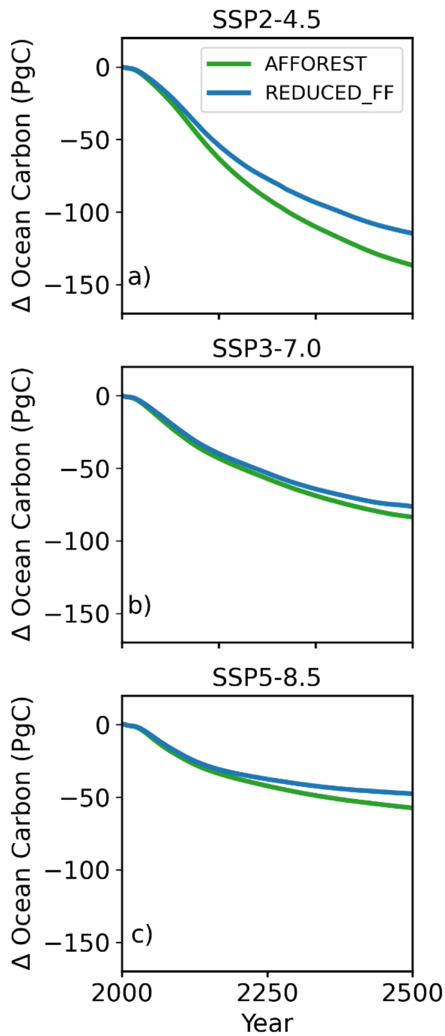


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**Figure 6.** Changes in global total ocean carbon content in the AFFOREST (green; ΔAFFOREST) and REDUCED_FF (blue; Δ REDUCED_FF) cases relative to the FIXED_AGR case in the a) SSP2-4.5 b) SSP3-7.0 and c) SSP5-8.5 scenarios. The AFFOREST and REDUCED_FF cases have smaller ocean carbon than the FIXED_AGR case in the three SSP scenarios because of the reduction of atmospheric $CO_2$ in the AFFOREST and REDUCED_FF cases by afforestation and reduced fossil fuel emissions, respectively.

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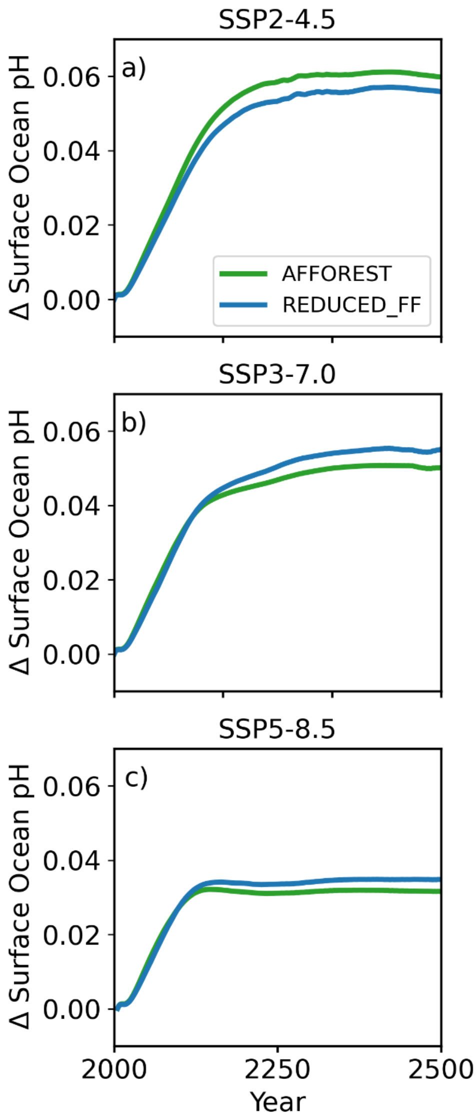


475 **Figure 7.** Changes in global mean surface ocean pH in the AFFOREST (green; ΔAFFOREST) and REDUCED_FF (blue; Δ REDUCED_FF) cases relative to the FIXED_AGR case in the a) SSP2-4.5 b) SSP3-7.0 and c) SSP5-8.5 scenarios. The AFFOREST and REDUCED_FF cases have larger surface ocean pH than the FIXED_AGR case because of the smaller ocean carbon content in AFFOREST and REDUCED_FF cases (Figure S6).

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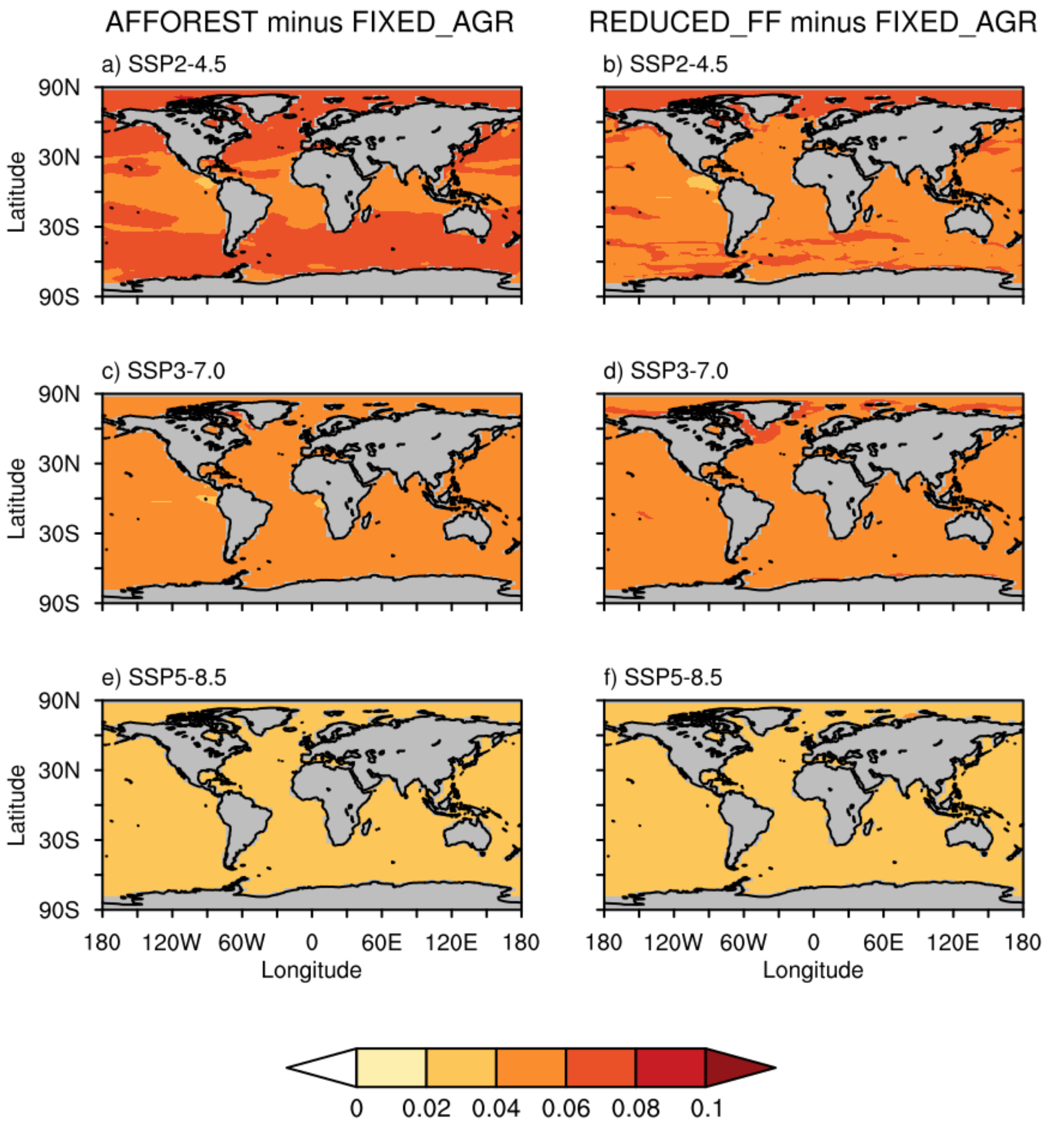


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485 **Figure 8.** The left (right) panel shows the spatial pattern of the difference in global mean surface ocean pH (averaged over 2471-2500) between AFFOREST (REDUCED_FF) and FIXED_AGR. The top, middle and bottom panels correspond to the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios, respectively. AFFOREST and REDUCED_FF cases have larger and similar surface ocean pH in all regions compared to the FIXED_AGR case in the three SSP scenarios.

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490 **Tables**

| | FIXED_AGR | AFFOREST | REDUCED_FF |
|---|---|---|---|
| Fossil fuel emissions | Follows three SSP scenarios (SSP2-4.5, SSP3-7.0 and SSP5-8.5) | Follows three SSP scenarios (SSP2-4.5, SSP3-7.0 and SSP5-8.5) | Follows emissions in three SSP scenarios (SSP2-4.5, SSP3-7.0 and SSP5-8.5) but CO2 emissions are reduced by the amount of carbon additionally stored on land in the AFFOREST simulation |
| Agricultural land fraction | Fixed at 2005 values | Set to zero from 2006 | Fixed at 2005 values |

**Table 1.** A summary of the simulations.