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Supplement of

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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Supplementary Information

SI TEXT S1: Spinup Simulation (PI_1750)

The spin up simulation PI_1750 consists of two stages: first is a 5000-year prescribed CO_2 simulation with an atmospheric CO_2 concentration of 280ppm and agricultural land corresponding to the year 1750. This is followed in the 2nd stage by a 2500-year zero emissions simulation with the same values for the agricultural land as in the first stage. The steady state values of atmospheric CO_2 concentration and surface air temperature (SAT) averaged over the last 30 years of the spin up simulation are 280.8 ppm and 13.2°C, respectively. The evolution of key climate and carbon cycle variables in PI_1750 are shown in Figure S2. Figure S2c and d shows the evolution of global mean precipitation and evaporation in PI_1750. The steady state value of global mean precipitation and evaporation is 1.05m yr^{-1}. The top of atmosphere net radiation and carbon fluxes approach zero at the end of PI_1750 (Fig. S2e, f).

SI TEXT S2: Historical Simulation (HIST_1750_2005)

The historical simulation starts from 1750 and ends in 2005 by prescribing fossil fuel emissions (Hoesly et al., 2018), fraction of agricultural land (cropland and pastureland) (Chini et al., 2014) and volcanic forcing (Crowley, 2000).The evolution of atmospheric CO_2 and SAT in our historical simulations are compared with the observations in Figure S3. The atmospheric CO_2 and SAT values averaged over the last 30 years (1976-2005) of HIST_1750_2005 are 349.1ppm and 13.5°C, respectively. In our simulations, the UVic model simulation underestimates atmospheric CO_2 and global mean SAT by 5ppm and 0.2°C, respectively. The evolution of other important parameters in HIST_1750_2005 are shown in Figure S4. The precipitation and evaporation are approximately the same as the preindustrial values of 1.05 m yr^{-1} (Figure S4e, f). The global total precipitation during the last 30 years (1976-2005) of our historical simulation is 1.05 m yr^{-1}, which is close to the estimate of 0.98 m yr^{-1} from satellite observations (Adler et al., 2017). The abrupt decreases in the top of the atmosphere (TOA) net radiation in the historical simulation (Figure S4e) corresponds to volcanic forcing. The sea ice area extent decreases from $2.23\times10^{13} m^2$ in the spinup simulation (averaged over the last 30 years of PI_1750) to $2.18\times10^{13} m^2$ during the historical simulation (averaged over the last 30 years (1976-2005) of the HIST_1750_2005 simulation).

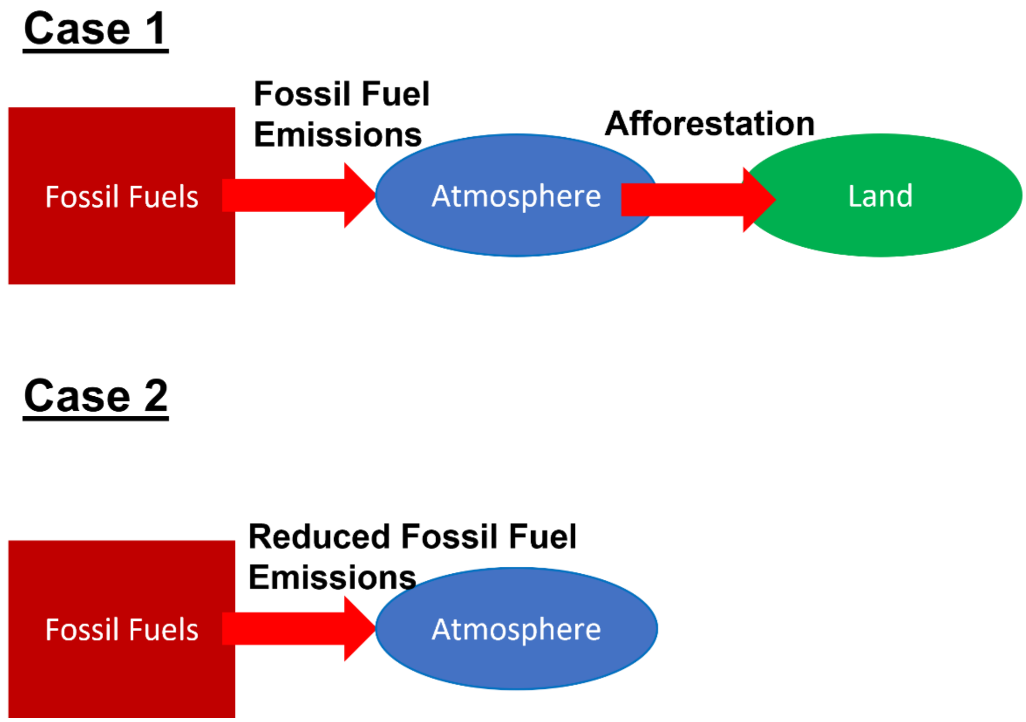

Figure S1. A schematic representation of the two cases used in our study to compare the climate and carbon cycle effects of afforestation and reduced fossil fuel emissions. In case 1, emissions follow three SSP scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5) and afforestation results in removal of carbon from the atmosphere. In case 2, emissions follow three SSP scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5), but fossil fuel CO_2 emissions are reduced by the same amount that is additionally stored on land by afforestation in case 1.

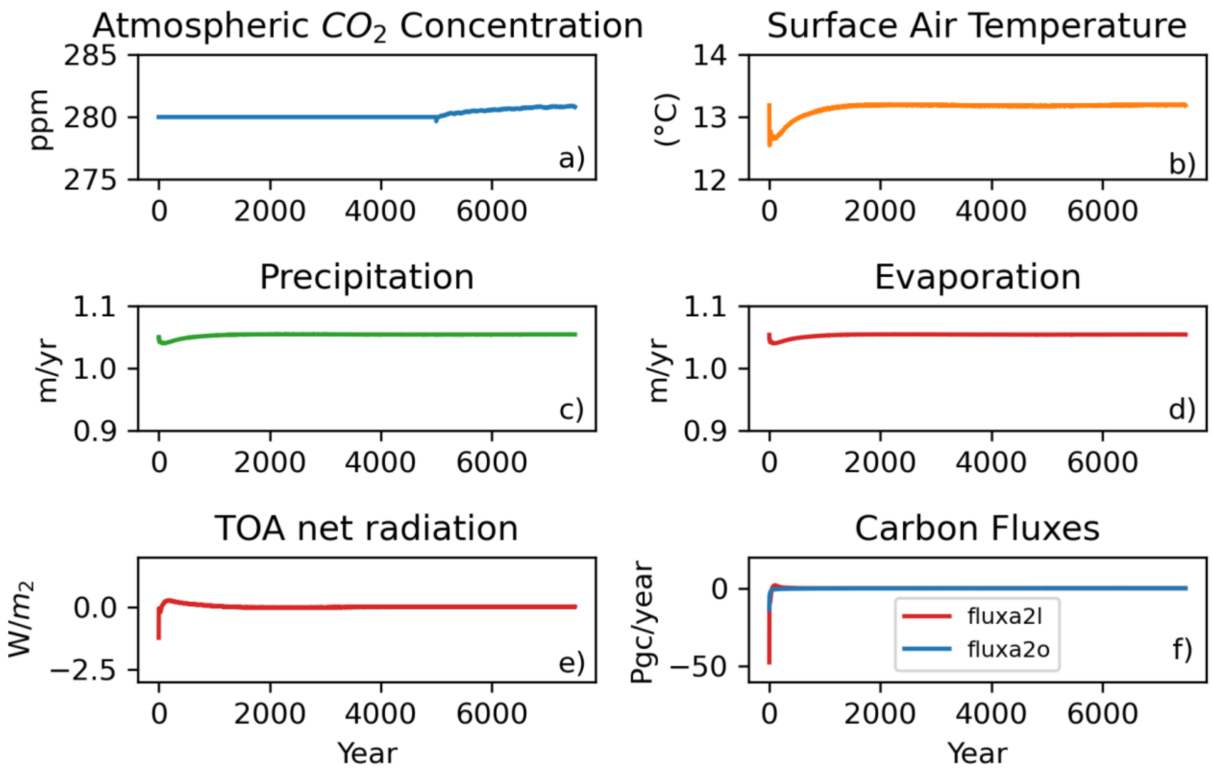

Figure S2. The evolution of a) global mean atmospheric CO_2 concentration, b) global mean surface air temperature, c) global mean precipitation, d) global mean evaporation, e) top of the atmosphere (TOA) net radiation and f) global mean atmosphere to ocean (fluxa2o; blue) and atmosphere to land carbon fluxes (fluxa2l; red) in the spinup simulation PI_1750. The equilibrium values of global mean atmospheric CO_2 and surface air temperature are 280.84ppm and 13.19°C respectively. The TOA net radiation and carbon fluxes approach zero at the end of PI_1750. The equilibrium value of global mean precipitation and evaporation is 1.05m yr^{-1}.

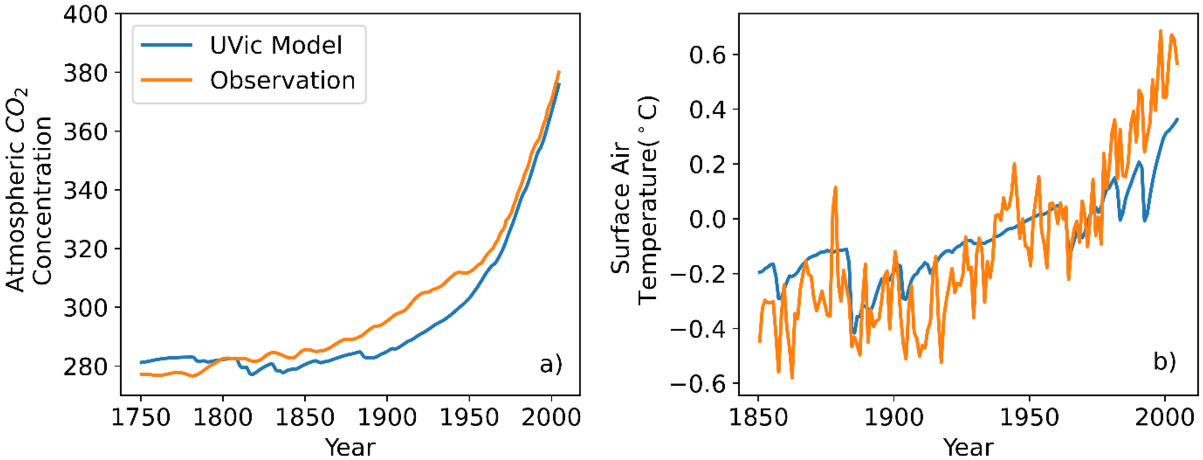

Figure S3. The evolution of global mean a) atmospheric CO_2 concentration and b) surface air temperature (SAT) in the historical simulation (HIST_1750_2005) and observations. The observations of atmospheric CO_2 concentrations and global surface air temperature are obtained from Rubino *et al* 2019 and Berkeley Earth Surface Temperatures (BEST) observations. In our historical simulation, the UVic model simulation underestimates atmospheric CO_2 and global mean SAT (averaged over 1976-2005) by 5ppm and 0.2°C, respectively.

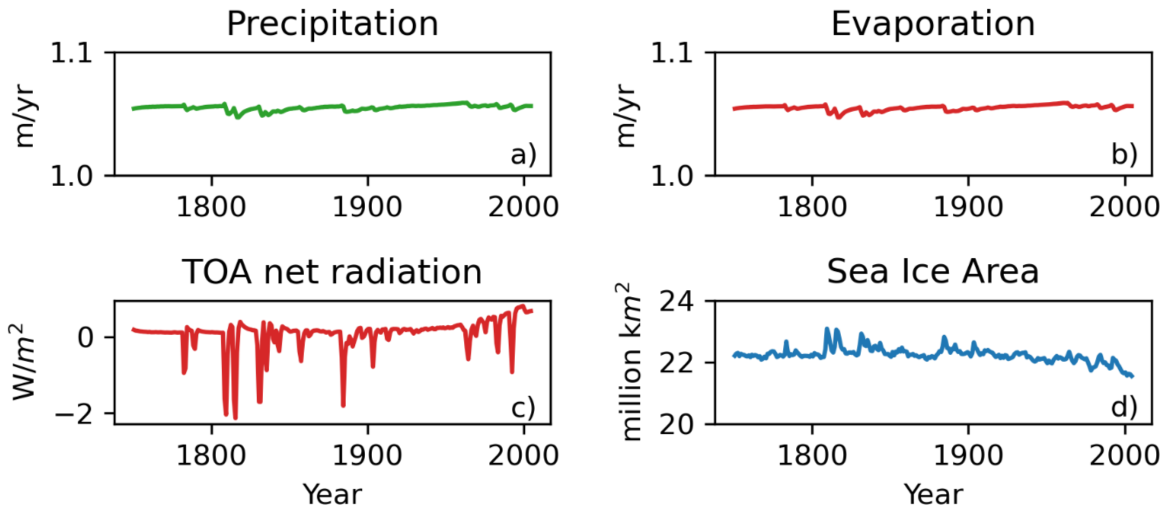

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Figure S4. The evolution of a) global mean precipitation, b) global mean evaporation, c) top of the atmosphere (TOA) net radiation, and d) global sea ice area in our historical simulation (HIST_1750_2005). The global mean precipitation and evaporation remain unchanged at the preindustrial state value of 1.05 m yr^{-1}. The abrupt decreases in the TOA net radiation in the historical simulation correspond to volcanic forcing. The sea ice area decreases from $2.23\times10^{13}m^2$ in the spinup simulation (averaged over the last 30 years of PI_1750) to $2.18\times10^{13}m^2$ in the last 30 years (1976-2005) of the historical simulation (HIST_1750_2005).

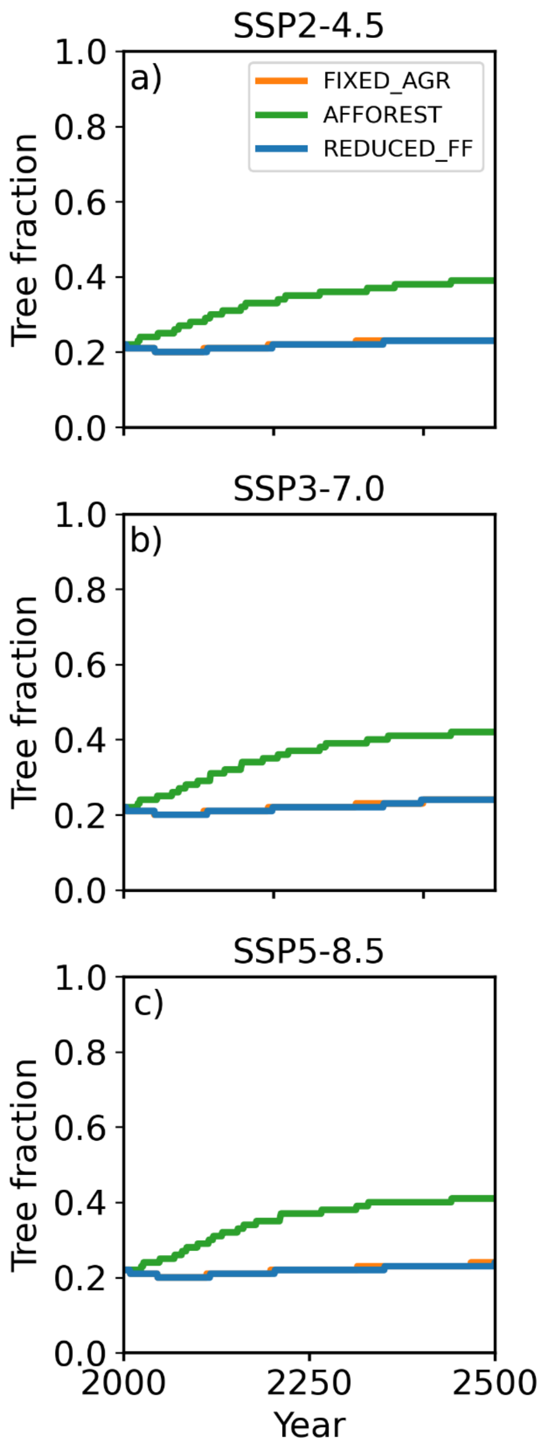


Figure S5. The evolution of tree fraction (sum of broad leaf trees and needle leaf trees) in the FIXED_AGR, AFFOREST and REDCUED_FF simulations for the a) SSP 2-4.5, b) SSP 3-7.0, and c) SSP 5-8.5 scenarios. In the AFFOREST case, agricultural land is set to zero after the year 2005. Therefore, forests regrow over the abandoned agricultural land resulting in a larger tree fraction in the AFFOREST case in the three SSP scenarios.

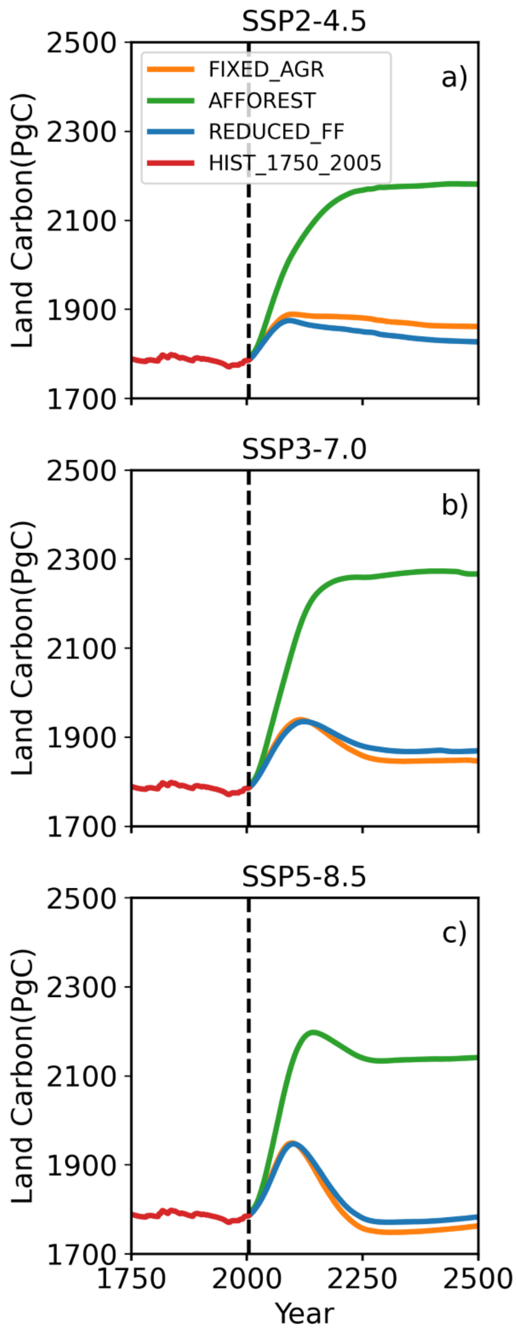


Figure S6. The evolution of global total land carbon in the FIXED_AGR, AFFOREST, REDUCED_FF, and HIST_1750_2005 simulations in the a) SSP2-4.5, b) SSP 3-7.0, and c) SSP 5-8.5 scenarios. In the AFFOREST case, the agricultural land is set to zero, and the forests are allowed to regrow after 2005. This results in larger carbon stored in land in the AFFOREST case in the three SSP scenarios.

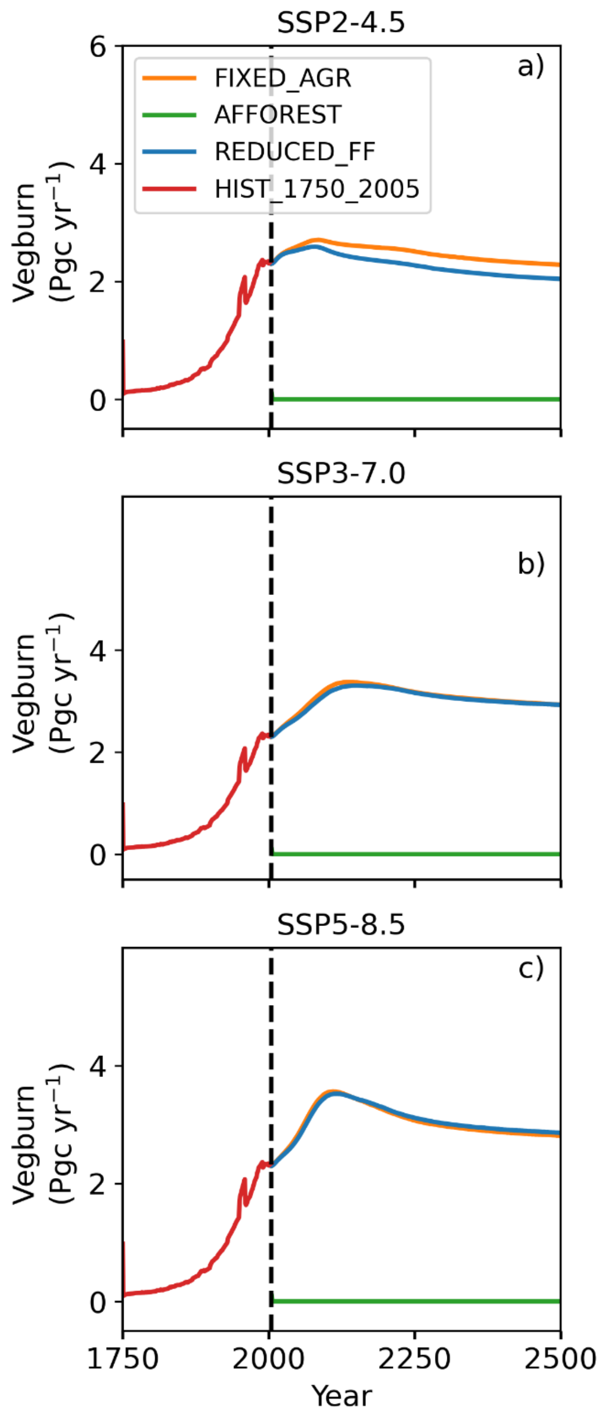


Figure S7. The evolution of vegetation burning flux (VEGBURN) in the FIXED_AGR, AFFOREST, REDUCED_FF, and HIST_1750_2005 simulations in the a) SSP2-4.5, b) SSP 3-7.0, and c) SSP 5-8.5 scenarios. During the historical period, VEGBURN represents the amount of carbon emitted into the atmosphere to expand and maintain the agricultural land fraction. In the AFFOREST case VEGBURN is zero because the agricultural land fraction is zero.

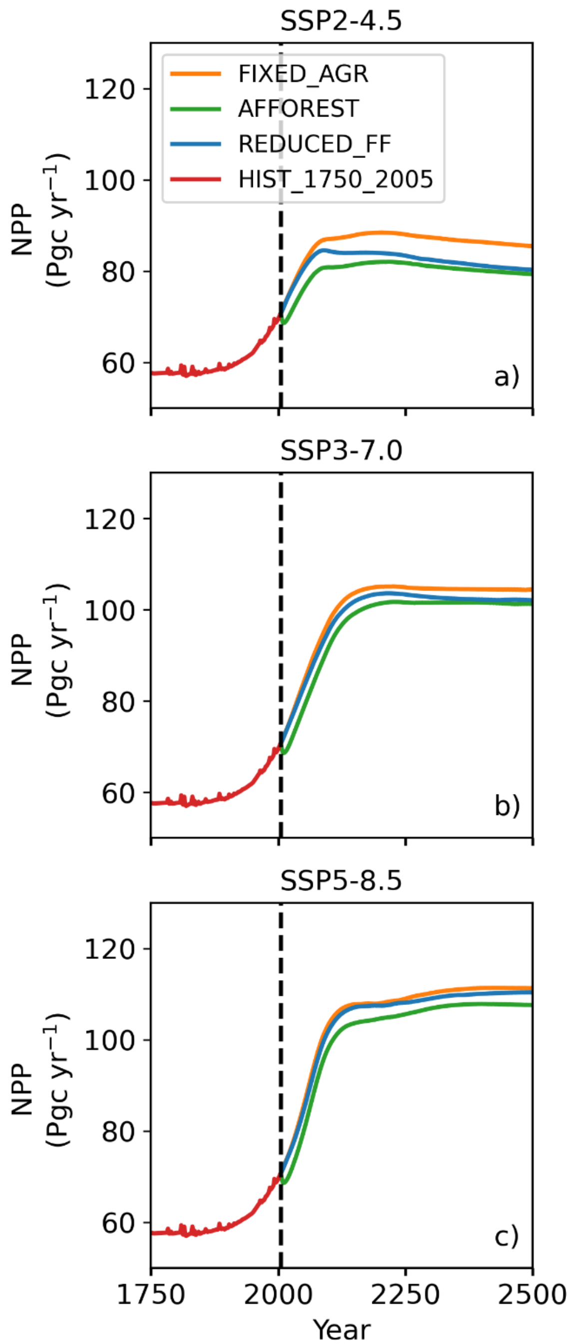


Figure S8. Evolution of the global land mean vegetation net primary productivity (NPP) in the FIXED_AGR, AFFOREST, REDUCED_FF, and HIST_1750_2005 simulations in the a) SSP2-4.5, b) SSP 3-7.0, and c) SSP 5-8.5 scenarios. NPP increases initially in all simulations because of the CO_2 fertilization effect, wherein elevated CO_2 concentrations lead to larger plant productivity. As the emissions are reduced to zero by 2250, NPP becomes relatively constant because of the absence of the CO_2 fertilization effect after 2250.

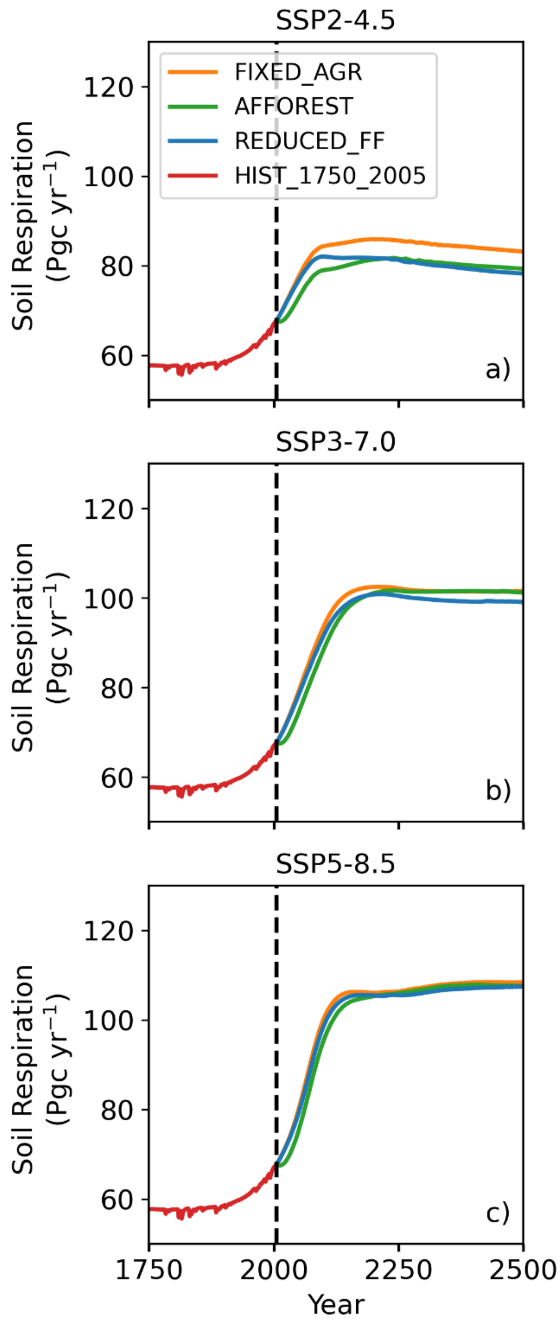


Figure S9. The evolution of global land soil respiration in the FIXED_AGR, AFFOREST, REDUCED_FF, and HIST_1750_2005 simulations in the a) SSP2-4.5, b) SSP 3-7.0, and c) SSP 5-8.5 scenarios. Soil respiration increases initially in all simulations because of the increase in temperature associated with the increase in atmospheric CO_2 concentrations and becomes relatively constant after the year 2250 in all simulations because emissions are zero after 2250.

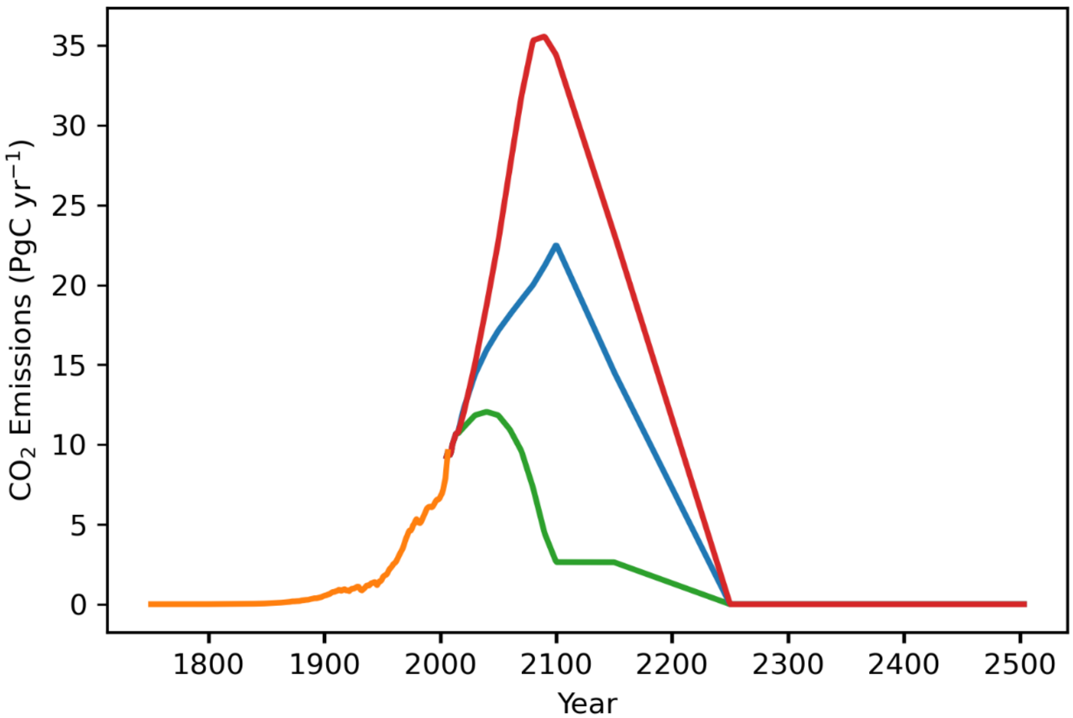


Figure S10. Historical and future projections of fossil fuel emissions in the SSP2-4.5, SSP3-7.0, SSP5-8.5 scenarios used in the current study (Meinshausen et al., 2020).

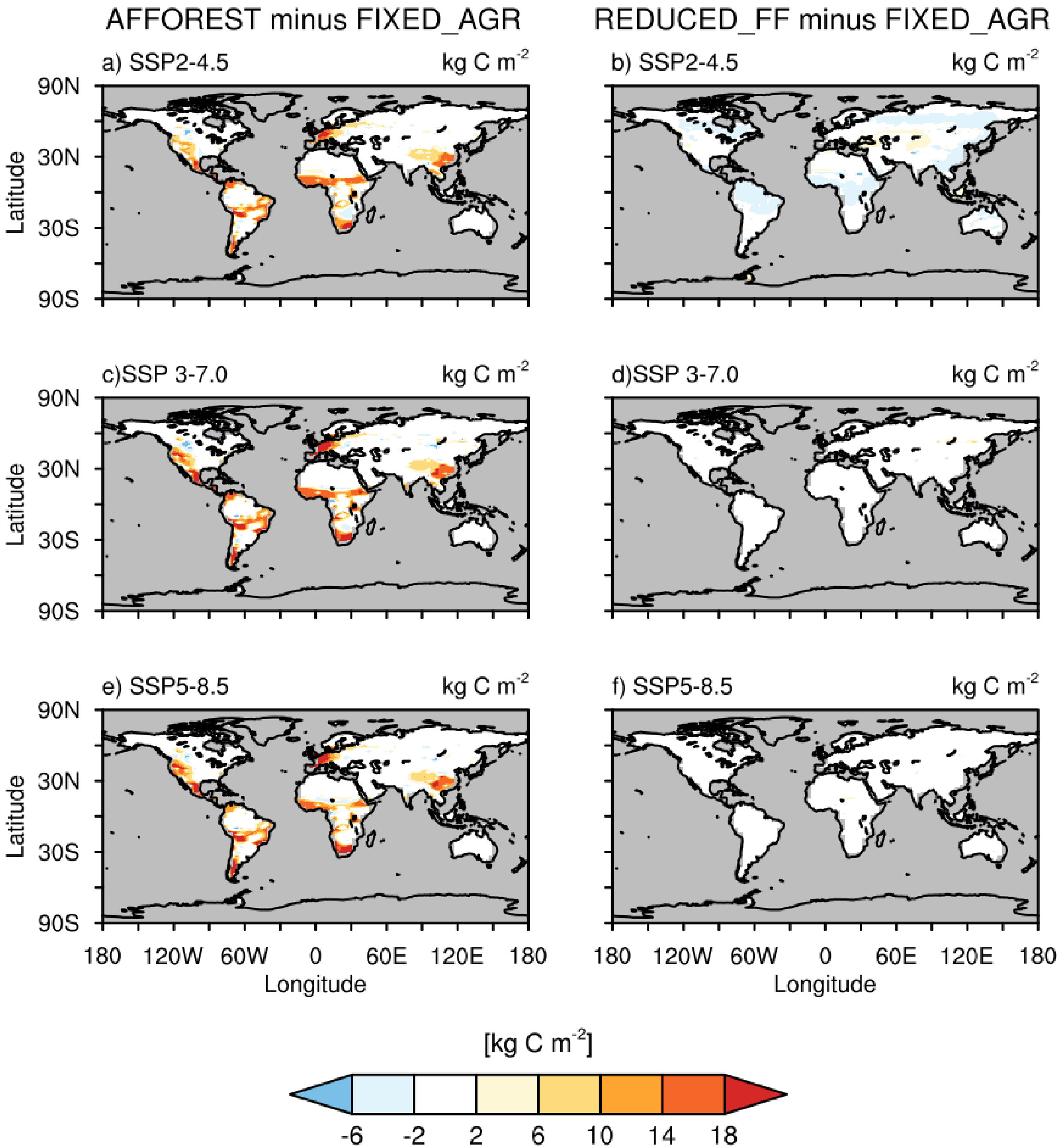


Figure S11. The left (right) panel shows the spatial pattern of the difference in total land carbon (averaged over 2471-2500) between the AFFOREST (REDUCED_FF) and FIXED_AGR simulations. The top, middle, and bottom panels correspond to the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively. The AFFOREST case has larger land carbon compared to the FIXED_AGR case in regions where forests regrow (Figure 2), while the REDUCED_FF case has similar land carbon as that of FIXED_AGR case in the three SSP scenarios.

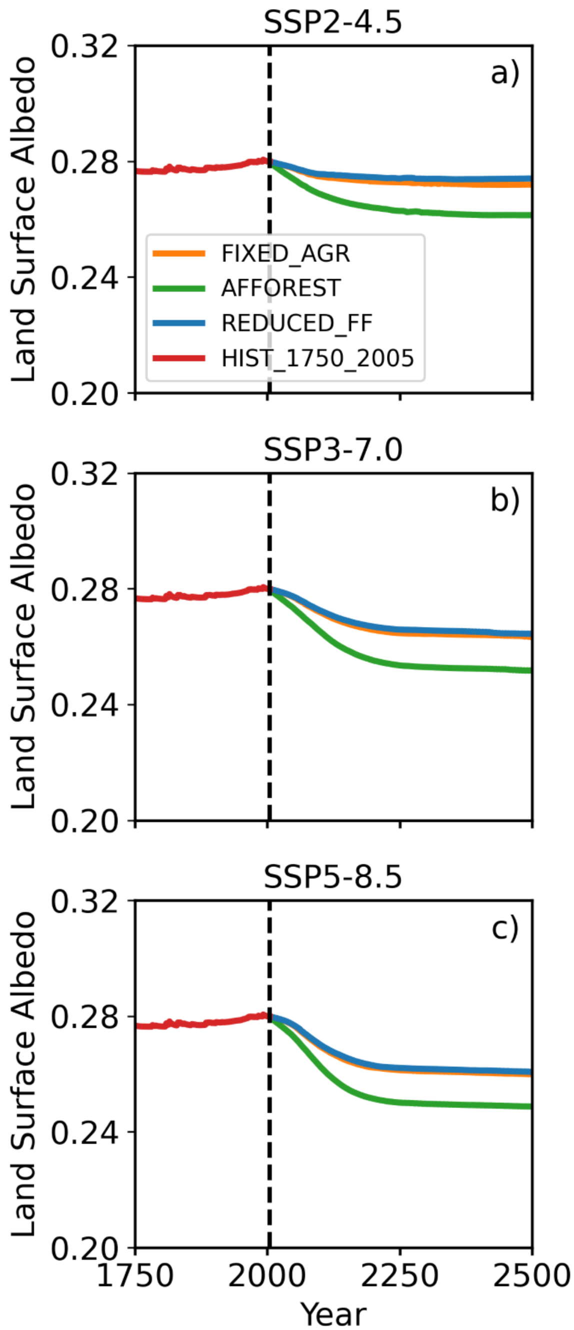


Figure S12. The evolution of land mean surface albedo in the FIXED_AGR, AFFOREST, REDUCED_FF and HIST_1750_2005 simulations in the a) SSP 2-4.5, b) SSP 3-7.0 and c) SSP 5-8.5 scenarios. In the AFFOREST case, forests are allowed to regrow over abandoned agricultural land after 2005. Since forests have a lower albedo compared to grasslands, land surface albedo is less in the AFFOREST case in the three SSP scenarios.

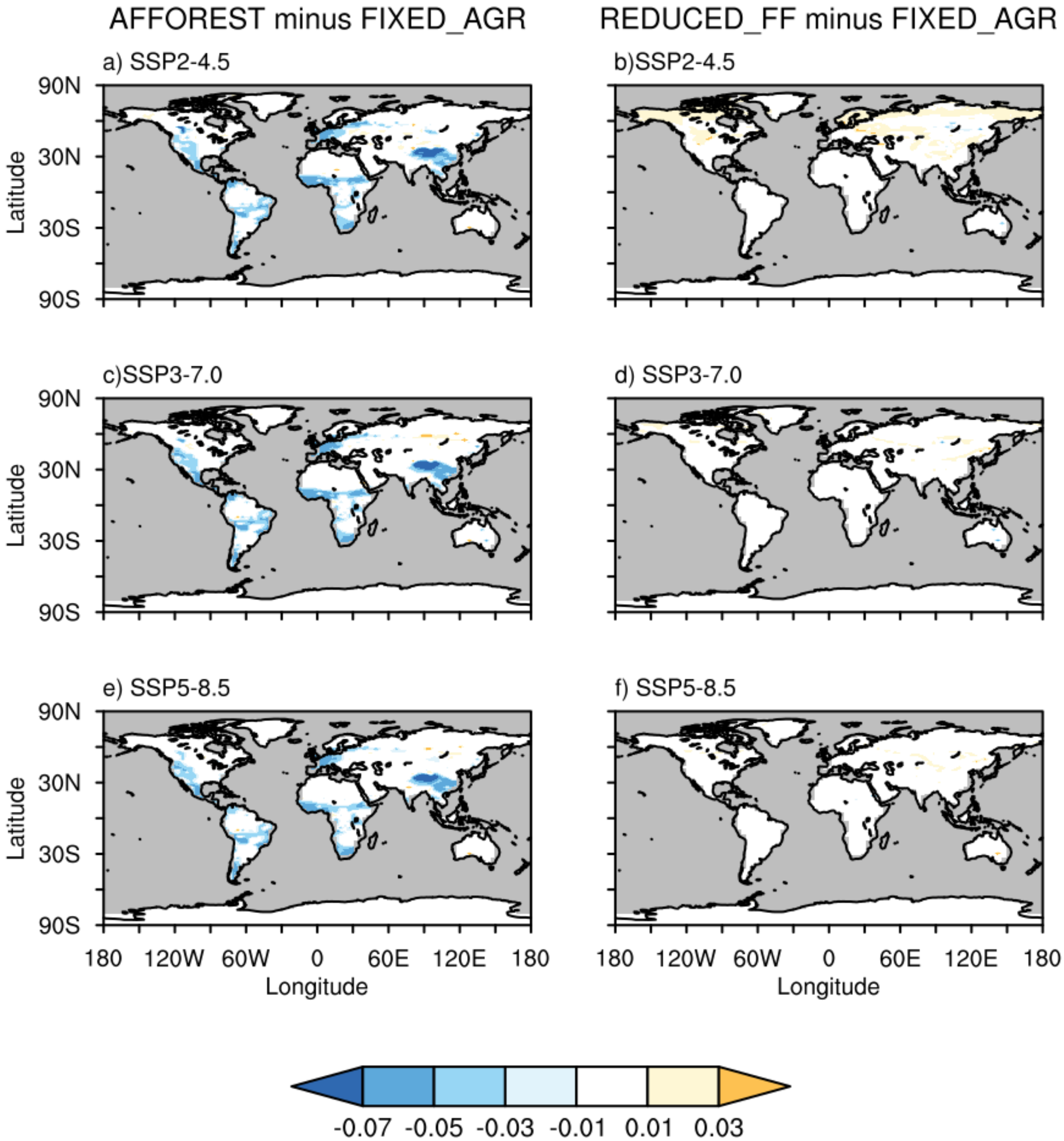


Figure S13. The left (right) panel shows the spatial pattern of the difference in land surface albedo (averaged over 2471-2500) between the AFFOREST (REDUCED_FF) and FIXED_AGR simulations. The top, middle and bottom panels correspond to the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios, respectively. The AFFOREST case has smaller land surface albedo compared to the FIXED_AGR case in regions where forest regrow, while the REDUCED_FF case has almost similar land surface albedo as that of the FIXED_AGR case in the three SSP scenarios.

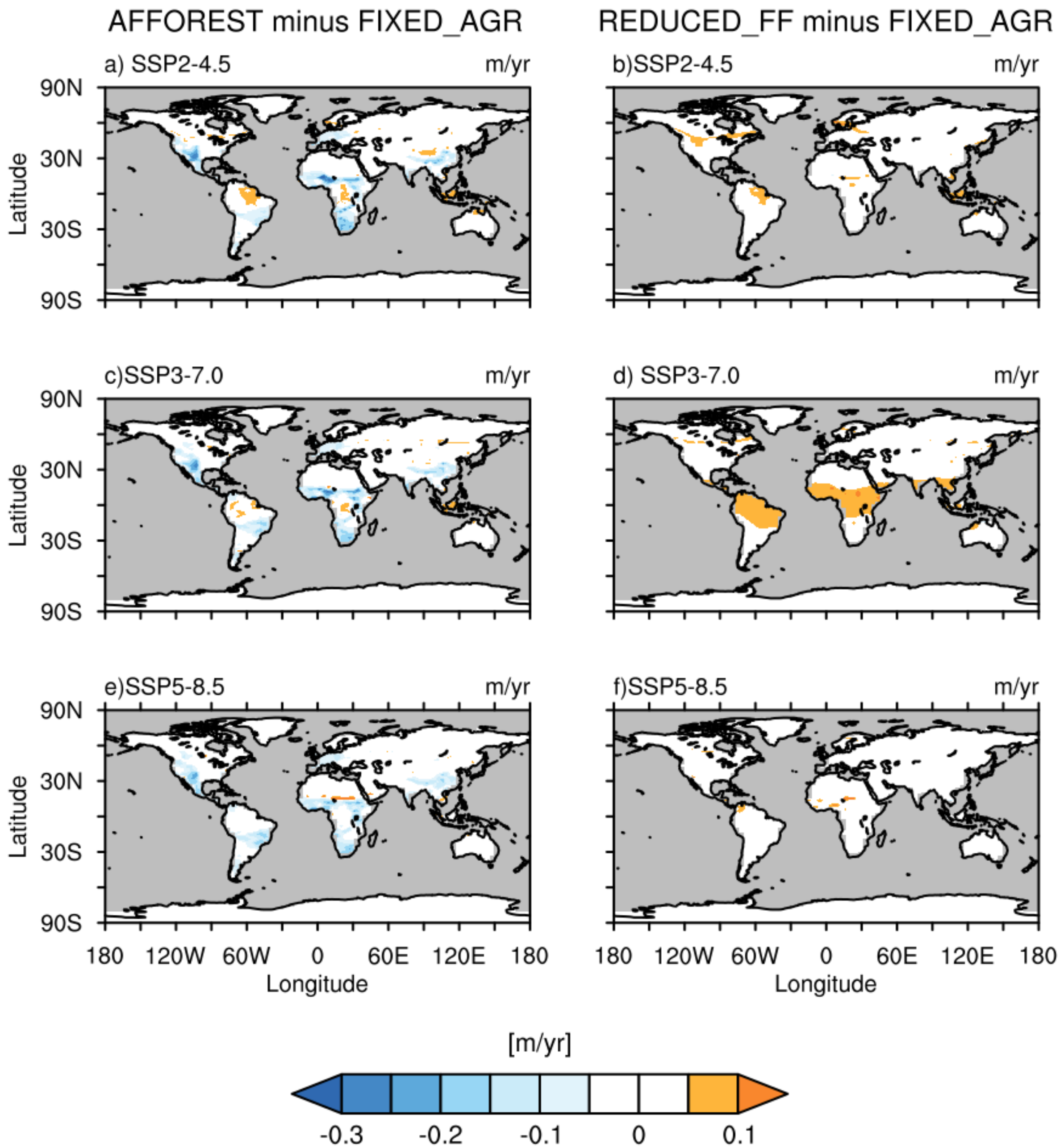


Figure S14. The left (right) panel shows the spatial pattern of the difference in evapotranspiration (averaged over 2471-2500) between the AFFOREST (REDUCED_FF) and FIXED_AGR simulations. The top, middle, and bottom panels correspond to the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively. The AFFOREST case has a smaller evapotranspiration compared to the FIXED_AGR case in regions where forests regrow, while the REDUCED_FF case has larger or similar evapotranspiration compared to the FIXED_AGR case everywhere in the three SSP scenarios.

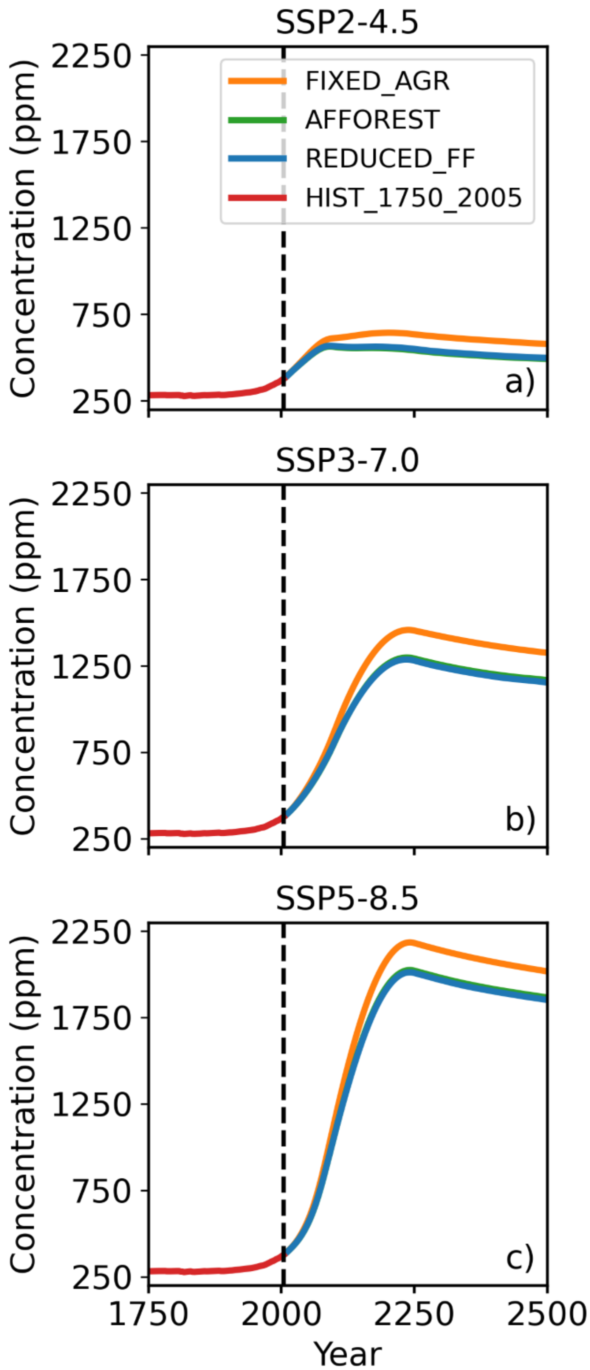
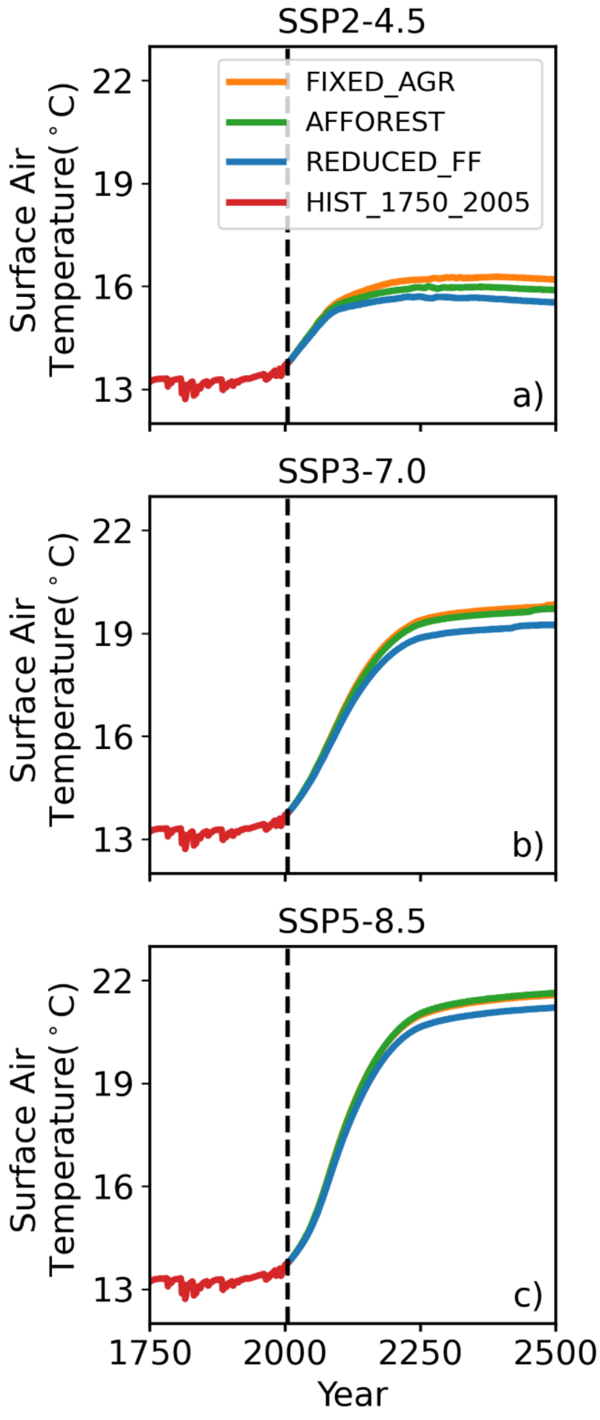


Figure S15. The evolution of global mean atmospheric CO_2 concentration in the FIXED_AGR, AFFOREST, REDUCED_FF and HIST_1750_2005 simulations in the a) SSP2-4.5, b) SSP3-7.0, and c) SSP5-8.5 scenarios. The AFFOREST and REDUCED_FF cases simulate similar atmospheric CO_2 concentrations because the same amount of carbon is removed from the atmosphere in these cases.



150 **Figure S16.** The evolution of global mean surface air temperature (SAT) in the FIXED_AGR, AFFOREST, REDUCED_FF and HIST_1750_2005 simulations in the a) SSP2-4.5, b) SSP3-7.0, and c) SSP5-8.5 scenarios. The AFFOREST case simulates larger warming than the REDUCED_FF case in all three scenarios because of the offset between the cooling effect of removal of carbon from the atmosphere and the warming effect of the regrowth of trees in the AFFOREST case.

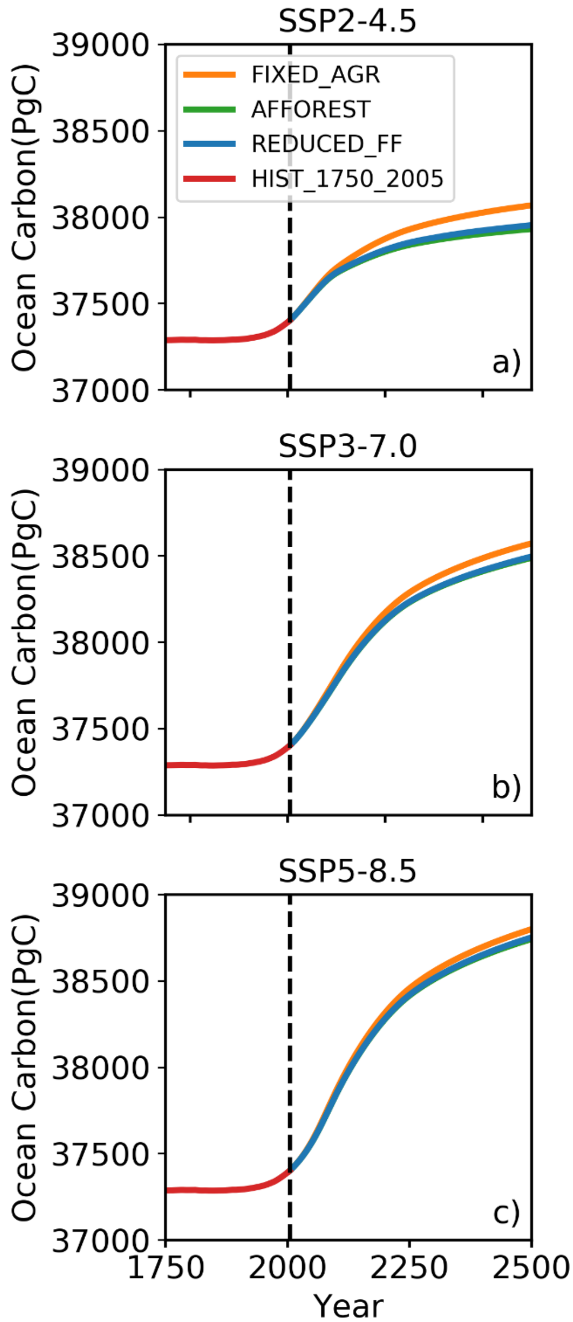


Figure S17. The evolution of ocean carbon content in the FIXED_AGR, AFFOREST, REDUCED_FF and HIST_1750_2005 simulations in the a) SSP2-4.5, b) SSP3-7.0, and c) SSP5-8.5 scenarios. Ocean carbon content is less in the AFFOREST and REDUCED_FF cases compared to the FIXED_AGR case because of the lower atmospheric CO_2 concentration in the AFFOREST and REDUCED_FF cases.

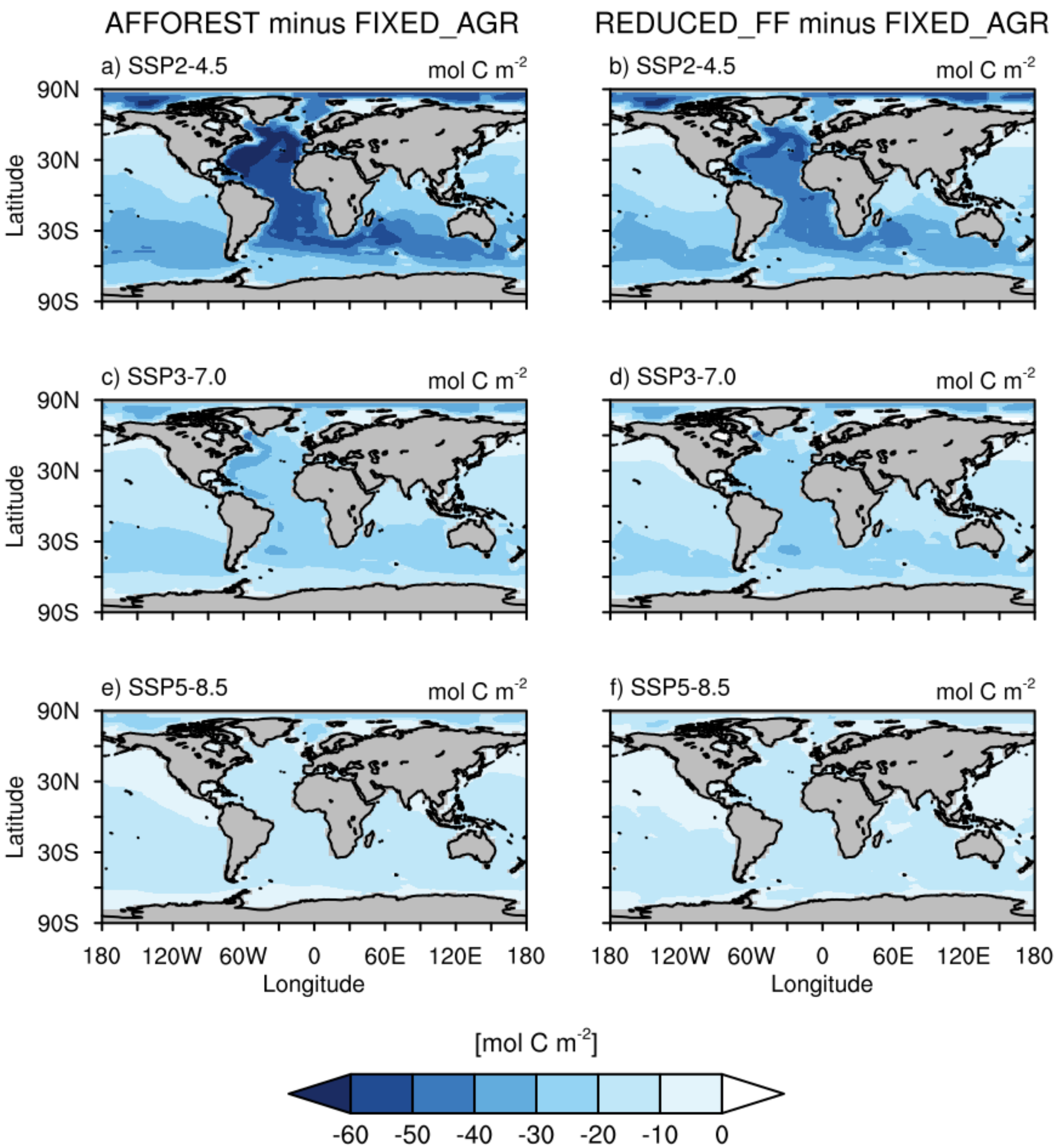


Figure S18. The left (right) panel shows the spatial pattern of the difference in vertically integrated ocean carbon content (averaged over 2471-2500) between the AFFOREST (REDUCED_FF) and FIXED_AGR. The top, middle and bottom panels correspond to the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively. Both AFFOREST and REDUCED_FF cases have smaller ocean carbon content than the FIXED_AGR case because the reduced atmospheric CO_2 concentration in the AFFOREST and REDUCED_FF cases result in smaller ocean carbon to maintain equilibrium with the atmosphere.

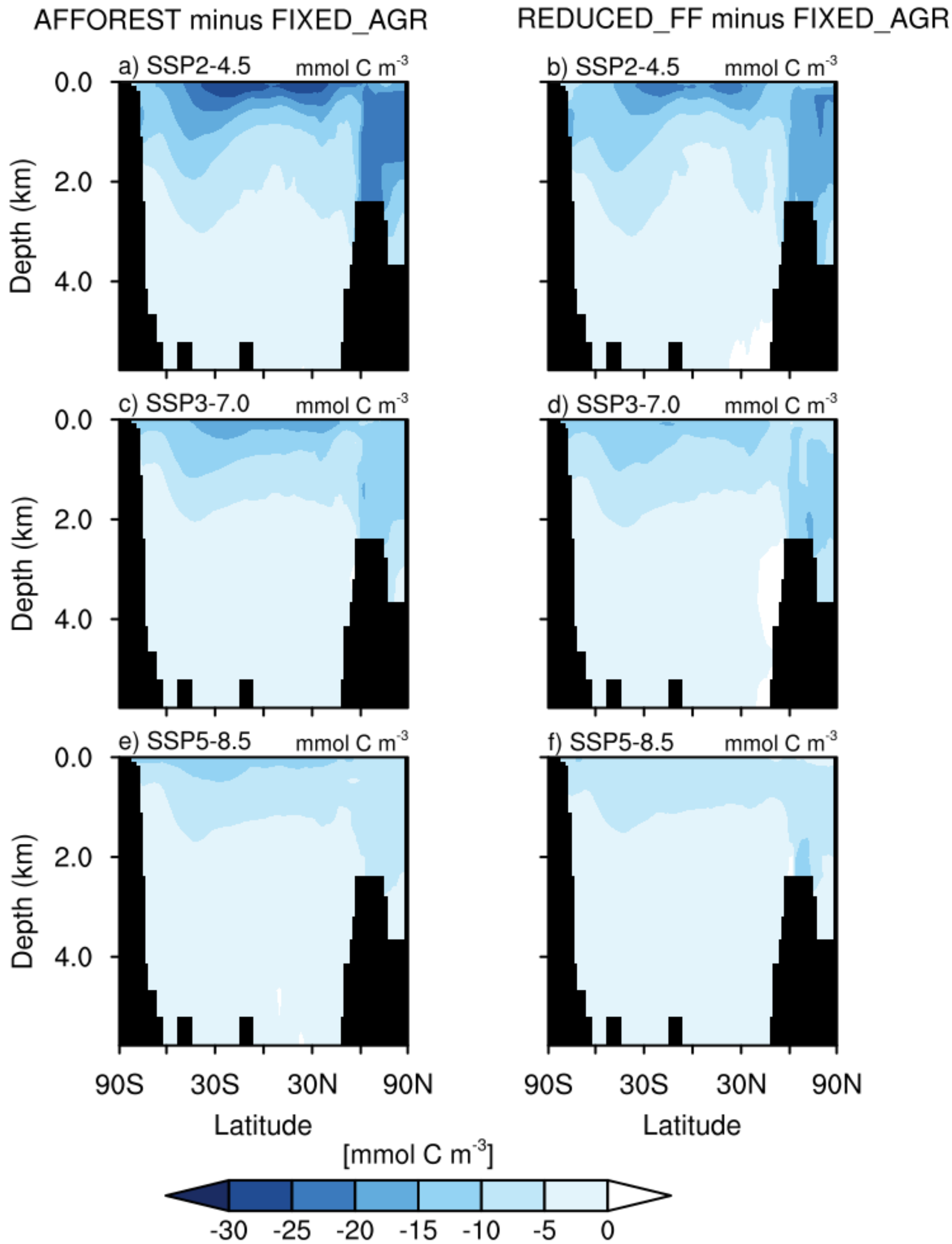


Figure S19. The left (right) panel shows the spatial pattern of the difference in zonally averaged vertical ocean carbon content (averaged over 2471-2500) between the AFFOREST (REDUCED_FF) and FIXED_AGR cases. The top, middle, and bottom panels correspond to the SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively. The AFFOREST and REDUCED_FF cases simulate lower ocean carbon content than the FIXED_AGR case because the reduced atmospheric CO_2 concentration in the AFFOREST and REDUCED_FF cases result in smaller ocean carbon to maintain equilibrium with the atmosphere.

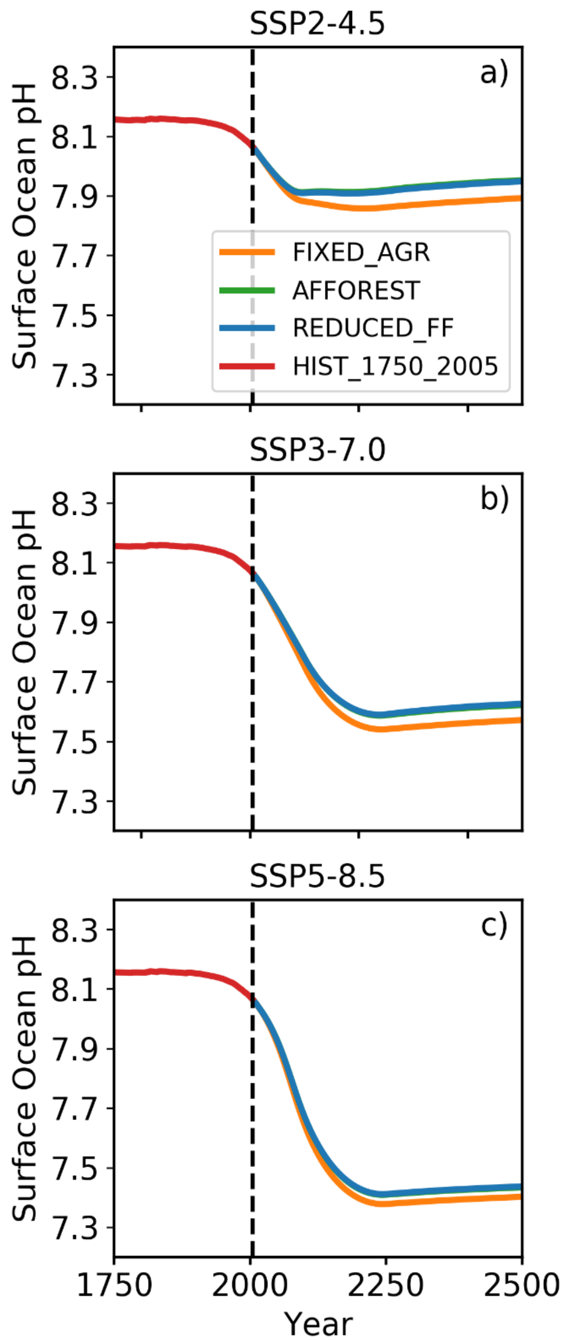


Figure S20. The evolution of global mean surface ocean pH in the FIXED_AGR, AFFOREST, REDUCED_FF and HIST_1750_2005 simulations in the a) SSP2-4.5, b) SSP3-7.0, and c) SSP5-8.5 scenarios. Surface ocean pH is larger in the AFFOREST and REDUCED_FF cases compared to the FIXED_AGR case because of the smaller ocean carbon content in the AFFOREST and REDUCED_FF cases.

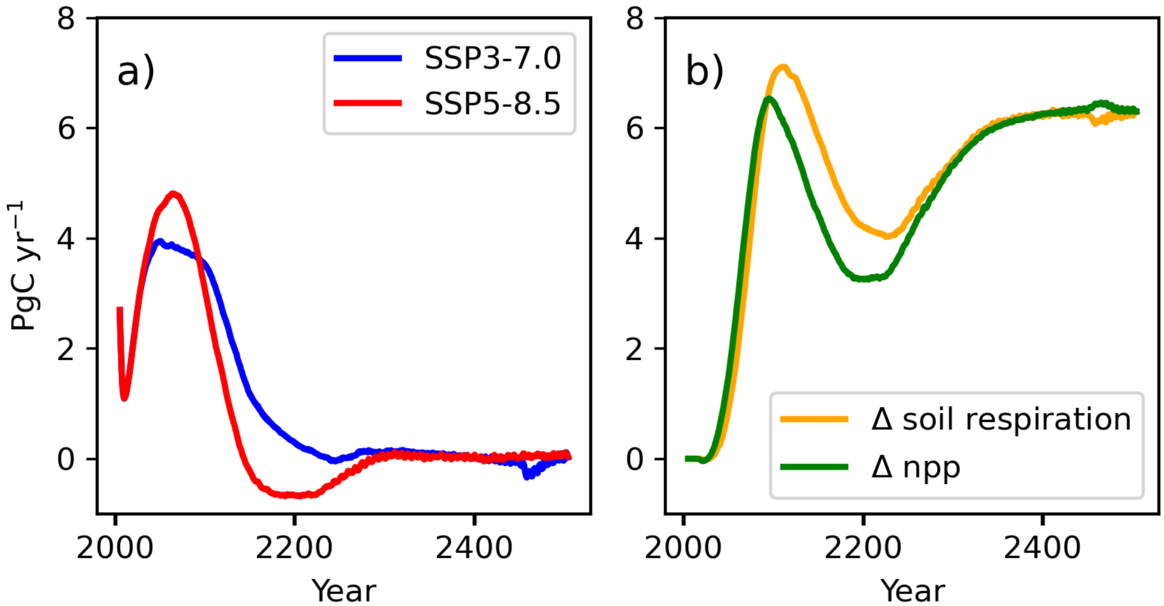


Figure S21. Panel (a) shows the evolution of the mean atmosphere to land carbon fluxes in the AFFOREST case of the SSP3-7.0 (blue) and SSP5-8.5 (red) scenarios. Panel (b) shows the difference in soil respiration (orange) and net primary productivity (green) between the AFFOREST case of the SSP5-8.5 and SSP3-7.0 scenarios. As shown in (a), the atmosphere to land carbon flux is larger in the SSP3-7.0 scenario compared to SSP5-8.5 during 2100-2300, because the difference in soil respiration in the AFFOREST case between the SSP5-8.5 and SSP3-7.0 scenarios is more than the corresponding difference in net primary productivity during this period. Therefore, the additional land carbon storage in the SSP3-7.0 scenario is larger than in the SSP5-8.5 scenario.

Tables

Parameter	Preindustrial State (PI_1750)	Historical State (HIST_1750_2005)
Atmospheric CO_2 (ppm)	280.8	349.1
Surface Air Temperature (ºC)	13.2	13.5
Surface ocean pH	8.15	8.09
Evaporation (m yr^{-1})	1.054	1.055
Precipitation (m yr^{-1})	1.054	1.055
Sea ice area (million km^2)	22.3	21.8
Land Carbon (PgC)	1789	1779
Ocean Carbon (PgC)	37287	37369
Land Surface Albedo	0.28	0.28

Table S1. Key climate and carbon cycle variables averaged over the last 30 years of the PI_1750 and HIST_1750_2005 simulations which represent the preindustrial and recent (1976-2005) state of the climate system, respectively.

	SSP2-4.5			SSP3-7.0			SSP5-8.5		
	FIXED_AGR	AFFOREST	REDUCED_FF	FIXED_AGR	AFFOREST	REDUCED_FF	FIXED_AGR	AFFOREST	REDUCED_FF
Atmospheric CO_2 (ppm)	231	144	150	982	823	810	1675	1523	1509
Surface Air Temperature (°C)	2.7	2.3	2	6.3	6.2	5.7	8.0	8.0	7.6
Surface ocean pH	-0.2	-0.14	-0.14	-0.52	-0.47	-0.47	-0.69	-0.66	-0.65
Land Carbon (PgC)	82	402	48	68	487	89	-18	361	1.9
Ocean Carbon (PgC)	694	559	580	1191	1109	1116	1417	1360	1369
Land Surface Albedo	-0.008	-0.02	-0.006	-0.016	-0.028	-0.016	-0.02	-0.031	-0.019

Table S2. Changes in the key climate and carbon cycle variables averaged over 2471-2500 of FIXED_AGR, AFFOREST and REDUCED_FF simulations in three SSP scenarios with respect to the average over 1976-2005 of HIST_1750_2005.

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