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# The Effectiveness of Agricultural Carbon Dioxide Removal using the University of Victoria Earth System Climate Model

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**Abstract.** A growing body of evidence suggests that to achieve the temperature goals of the Paris Agreement, carbon dioxide removal (CDR) will likely be required in addition to massive carbon dioxide ($CO_2$) emissions reductions. Nature-based CDR, which includes a range of strategies to sequester carbon in natural reservoirs, could play an important role in efforts to limit climate warming to well below 2°C above preindustrial levels. Agricultural CDR could enhance soil carbon sequestration, though the climate efficacy of such methods remains uncertain. Here, we use an intermediate complexity climate model to perform simulations of agricultural CDR in the form of soil carbon sequestration at a range of possible rates for different costs under three future emissions scenarios. We found that plausible levels of agricultural CDR were able to reduce $CO_2$ concentration by 5-19 ppm and global surface air temperature by 0.02-0.10°C by the end of century. This temperature decrease was non-linear with respect to cumulative removals, as any carbon removed remained part of the active carbon cycle, lessening the climate benefit compared to if the removed carbon was permanently stored in geological reservoirs. CDR was found to be more effective at reducing surface air temperature in low emissions scenarios, but less effective at reducing atmospheric $CO_2$, compared to high emissions scenarios. This was because the weaker $CO_2$ sinks in a high $CO_2$ world had a more muted response to removal, so a substantially higher proportion of carbon was removed from the atmosphere for a given amount of CDR in a higher emissions scenario. The enhanced temperature response to CDR in lower emissions scenarios was due to the logarithmic response of radiative effects to changes in $CO_2$, where at low atmospheric $CO_2$ concentrations, small changes in $CO_2$ are more effective at changing the global radiative balance than at higher $CO_2$ concentrations. CDR was substantially more effective when implemented at a higher rate, as CDR makes a proportionally larger difference in a climate with lower cumulative air fraction of $CO_2$. Land and soil carbon responses were driven by the scenario-dependent balances between the impacts of CDR on primary productivity from $CO_2$ fertilization, and the impacts on soil respiration from increased soil carbon availability and global temperatures.

## 1 Introduction

To meet the goals of the Paris Agreement and limit warming to 2°C above the pre-industrial temperature, there must be a massive reduction in carbon dioxide ($CO_2$) emissions as well as the implementation of carbon dioxide removal (CDR) from the atmosphere (Rogeli et al., 2021). Nature-based climate solutions (NbCS) are methods of CDR which enhance carbon storage beyond its natural level in natural and managed ecosystems, such as agriculture. Sequestering carbon in cropland

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and pasture land could act as a significant carbon sink in the near future while policies for emissions reductions are enacted, and to contribute to a long-term negative emissions strategy (Paustian et al., 2019). Indeed, agriculture has some of the most important mitigation options currently available as it can deliver CDR using existing farming practices, substitute fossil fuels, and maintain food security without requiring the massive land use changes that would be needed for afforestation (Smith et al., 2013; Nabuurs and Coauthors, 2022; Shukla and Coauthors, 2022).

Agriculture as a NbCS works through reducing emissions of greenhouse gases and direct carbon sequestration in to soil. Enhancing soil carbon storage, through protecting existing carbon pools and rebuilding depleted ones, has the potential to provide over a quarter of the nature-based CDR required to keep climate warming below 2°C above preindustrial levels (Bossio et al., 2020). Soil carbon sequestration in croplands and grazing lands has the technical potential to sequester 0.38-9.34 $GtCO_2eq$ $yr^{-1}$ between 2020 and 2050 (Roe et al., 2019). Collectively the components of agricultural CDR, such as nutrient management, biochar, agroforestry, and other management strategies, have been estimated to have the mitigation potential of 3.0-8.5 $GtCO_2eq$ $yr^{-1}$ by 2050 (Griscom et al., 2017; Brack and King, 2021; Nabuurs and Coauthors, 2022). These estimates were derived based on cost of implementation. They estimate that 3.0 $GtCO_2eq$ $yr^{-1}$ of CDR can be achieved through agriculture by 2050 for under 100 USD per $tCO_2eq$ $yr^{-1}$, while 8.5 $GtCO_2eq$ $yr^{-1}$ can be achieved for higher costs using frontier technologies, with safeguard constraints for food security and biodiversity (Griscom et al., 2017; Paustian et al., 2019; Brack and King, 2021). The Intergovernmental Panel on Climate Change 6th Assessment Report estimates likely agricultural CDR potential to be 4.1±1.6 $GtCO_2eq$ $yr^{-1}$ by 2050 Nabuurs and Coauthors (2022). Therefore, agricultural CDR of 3.0, 4.1, and 8.5 $GtCO_2eq$ $yr^{-1}$ by 2050 represent a range possible sequestration rates through low-, moderate-, and high- cost removal strategies and will encompass much of the analysis in this study.

Previous studies on the potential of agriculture as a NbCS have primarily focused on either regional analysis of soil carbon sequestration from sustainable farming, or on a specific component of agricultural CDR (such as biochar, microbial addition, conservation tillage, and regenerative agriculture) (Matthews et al., 2004; Chen et al., 2023; Tao et al., 2023; Elkhlifi et al., 2023; ur Rehman et al., 2023; Tan and Kuebbing, 2023; Mason et al., 2023; T.M. et al., 2023; Wiltshire and Beckage, 2023). This study aims to explore the global impacts and effectiveness of agricultural CDR at varying rates, using a similar approach to Matthews et al. (2022), who simulated carbon sequestration through reforestation under varying emissions scenarios. In their study, they expanded forest area to such a point that the carbon sequestered represented the maximum possible CDR through reforestation by 2050, after which the sequestered carbon was slowly returned to the atmosphere. They demonstrated that the expansion of land carbon storage decreases and delays the peak warming if implemented alongside aggressive emissions reductions. If implemented alongside less ambitious emissions reductions, warming continues until the end of the century but with a slower increase in warming. Therefore, temporary carbon storage is only effective in preventing global temperatures overshooting the 2°C target Paris Agreement if they are implemented alongside large emissions reductions (Canadell et al., 2023). Since most methods of agricultural carbon storage are also relatively short-term, with the exception of biochar pyrogenic carbon for which the lifetime is 10-100 times that of biomass, agricultural CDR would likely also require implementation alongside emissions reductions to be effective (Lehmann et al., 2021).

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While agriculture has potential as a nature-based climate solution, there is a substantial knowledge gap on the impacts on the climate system, and indeed the capacity of the land to support the agriculture in a changing climate (Keller et al., 2018; Seddon et al., 2020; Canadell et al., 2023; Nabuurs and Coauthors, 2022). While several studies have explored the carbon sequestration potential of agriculture, to our knowledge, no study has quantified the impact this form of CDR would have on the climate, such as how it would influence temperature, carbon storage in soil and vegetation, carbon fluxes, and non-$CO_2$ climate effects. The objective of this study is to expand on the work of Matthews et al. (2022), using simulations of agricultural CDR at a range of rates reflecting the realistic costs of implementation.

## 2 Methodology

To explore the impacts of agricultural CDR on the global climate, this study uses simulations designed to represent realistically-possible CDR from agriculture in an intermediate complexity global climate model. The simulations were performed using the University of Victoria Earth System Climate Model (UVic ESCM) version 2.10.

### 2.1 Model Description

The UVic ESCM is an intermediate-complexity global climate model, capable of simulating Earth's climate for long timescales at a lower computational cost, making it suitable for multi-century climate processes such as carbon cycle feedbacks (Weaver et al., 2001; Eby et al., 2009; Mengis et al., 2020). The UVic ESCM is one of the more complex of the intermediate complexity models, owing to its moderately high horizontal resolution in all model components (3.6°x1.8°), presence of sea-ice with rheology, fully coupled ocean model, and sediment processes. It has the same level of complexity of a general circulation model with the exception of the model atmosphere, which is heavily simplified to enhance computational efficiency, thus rendering it an intermediate complexity model. The current model version, 2.10, performs well with regards to changes in historical temperature and carbon fluxes (Mengis et al., 2020). Published biases in the UVic ESCM version 2.10 include too large vegetation density in the tropics, too large changes of ocean heat content, and too low oxygen utilisation in the Southern Ocean (Mengis et al., 2020).

The atmospheric component of the UVic ESCM is a two-dimensional energy-moisture balance model using thermodynamics instead of dynamics, parameterising atmospheric heat and moisture transport with diffusion (Fanning and Weaver, 1996). Wind velocity is prescribed based on NCAR/NCEP reanalysis data for monthly climatology (Eby et al., 2013). Using the prescribed wind fields, moisture, momentum, and heat fluxes are calculated in the model. Transient wind velocities are calculated based on anomalous surface pressure, caused by anomalies in surface temperature relative to the pre-industrial state (Weaver et al., 2001). The model does not simulate clouds, but instead produces rain or snow when relative humidity reaches 85%.

The oceanic component of the UVic ESCM is Modular Ocean Model 2 (MOM2), a fully three-dimensional ocean general circulation model consisting of 19 vertical levels, varying in vertical resolution from 50 m near the surface, to 500 m at depth (Bitz et al., 2001). The sea-ice component is a dynamical and thermodynamical model that is coupled to the ocean model and atmosphere model.

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The land component of the model contains an elaborate representation of the carbon cycle. The land component is made up of a surface model, which is a simplified version of the Met Office Surface Exchange Scheme (MOSES), coupled to the vegetation model Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) (Meissner et al., 2003). Carbon fluxes are calculated in the MOSES model, which then modifies the land, soil, and vegetation carbon pools (Matthews et al., 2004). TRIFFID simulates the soil carbon and coverage of five plant functional types: broadleaf tree, needleleaf tree, C3 grasses (cool season frost tolerant grasses), C4 grasses (warm season), and shrubs. In the TRIFFID model, agricultural crops are treated as C3 grasses. The PFTs space competition routine is based on the Lotka-Volterra equations (Cox, 2001; Meissner et al., 2003). In the UVic ESCM most recent update (2.10), one major improvement was to soil carbon and hydrology (Mengis et al., 2020).

### 2.2 Simulation Design

The UVic ESCM was spun up for 10,000 years with atmospheric $CO_2$ levels prescribed at 285 ppm corresponding to the year 1850. The model was then run from 1850-2020 using historical emissions, then run under three Shared Socioeconomic Pathway (SSP) marker scenarios from 2020-2100 using projected emissions (Riahi et al., 2017; Meinshausen et al., 2020).

The historical emissions and SSPs used here are shown in Figure 1. They describe potential pathways in which global societal and economic structure will change in the coming century and are used to derive corresponding greenhouse gas emissions based on policies. Under SSP1, future socioeconomic development would be highly sustainable, leading to net-negative $CO_2$ emissions by 2055 (Riahi et al., 2017). Under SSP2, future conditions are similar to those of today, with slow progress and regional rivalry inhibiting sustainable development. Under SSP5, socioeconomic development exploits fossil fuels, accelerating $CO_2$ emissions to over 120 $GtCO_2$ $yr^{-1}$ by 2100. For each SSP marker scenario, the radiative forcing by 2100 is 1.9, 4.5, and 8.5 W $m^{-2}$ respectively. SSPs 1-1.9, and 2-4.5 represent the most likely range of scenarios for global development. The data used here were taken from the International Institute for Applied System Analysis SSP database version 2.0 (Riahi et al., 2017; Meinshausen et al., 2020), which compiles historical emissions inventories (Velders et al., 2015; van Marle et al., 2017; Hoesly et al., 2018; Gütschow et al., 2016; Carpenter et al., 2014; Miller et al., 2014), and the future emissions from the SSP1-1.9 marker scenario (van Vuuren et al., 2017), SSP2-4.5 marker scenario (Fricko et al., 2017), and SSP5-Baseline marker scenario (Kriegler et al., 2017).

For each of the three SSP's (1, 2, and 5), four simulations were performed in this study: one with no additional agricultural CDR (control), one with agricultural CDR that can be achieved for low costs (3.0 $GtCO_2$ $yr^{-1}$ globally by 2050), one with moderate agricultural CDR (4.1 $GtCO_2$ $yr^{-1}$ by 2050), and one with agricultural CDR that can be achieved for high costs (8.5 $GtCO_2$ $yr^{-1}$ by 2050). These will hereafter be referred to as no-, low-, moderate-, and high-removal. Thus there are a total of twelve simulations in this study.

The agricultural CDR was achieved by prescribing an atmosphere-to-soil carbon flux in agricultural areas. This flux was defined to be in addition to the existing model geochemical fluxes that affect soil carbon: gross primary productivity, soil respiration, and litter flux. So any responses of these three fluxes to CDR is a legitimate biogeochemical response and was not externally prescribed.

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The prescribed agricultural atmosphere-to-soil CDR flux was weighted by the fractional area of agriculture in the cell, which is shown in Figure 2. The agricultural area fraction was not prescribed to change after 2020. The global total of the flux was prescribed to be time varying, increasing linearly from 0.0 $GtCO_2\ yr^{-1}$ at the year 2020 to 3.0, 4.1, or 8.5 $GtCO_2\ yr^{-1}$ by 2050, after which the CDR was held constant as shown in Figure 2.

## 3 Results and Discussion

### 3.1 CDR Impact on Atmospheric $CO_2$ Concentration and Temperature

Realistically-possible agricultural CDR was found in this study to have a tangible impact on $CO_2$ concentration and global surface air temperature (SAT) above the preindustrial value. As shown in Figure 3, by the end-of-century (EOC), in the low-removal scenarios, global SAT decreased by 0.02-0.04°C and $CO_2$ decreased by 5-7 ppm. Whereas high-removal resulted in cooling between 0.06-0.1°C and $CO_2$ decline by 14-19 ppm. This shows that while the impact on global SAT is not enormous, the response of the climate to agricultural CDR is scenario dependent, so the same amount of removal in one scenario does not yield the same $CO_2$ decrease or temperature decrease as another scenario even though the simulations were initiated from the same transient state.

### 3.2 Change in Surface Air Temperature and $CO_2$ Concentration Per Unit of CDR

To explore the effectiveness of CDR, this study used an adaptation of the Transient Climate Response to Emissions known as the Transient Climate Response to Removals (TCRR) (Matthews et al., 2009; Zickfeld et al., 2021). TCRR is defined as the change in SAT over a given period (in this case 2020-2100) divided by the cumulative $CO_2$ removed in that time. The TCRR for this study is shown in Figure 4a, and the response of atmospheric $CO_2$ to cumulative removal is shown in Figure 4b.

This study found that the TCRR from agriculture is strongly non-linear, with the SAT decrease substantially slowing as removal continues, and is also strongly dependent on the SSP scenario and rate of CDR (Figure 4a). For the higher emissions scenario scenario (SSP5), a given amount of CDR produced less of a temperature benefit than it did for the lower emissions scenarios (SSP1 and SSP2). For all scenarios, the effectiveness of CDR at reducing SAT was lower when CDR was implemented at a lower rate. For example, for SSP5, 50 GtC of CDR yields a temperature decrease of 0.2°C when implemented at the lowest rate, and 0.4°C for the highest rate.

The decline in atmospheric $CO_2$ due to agricultural CDR was also found to be non-linear, with the CDR becoming less effective at decreasing $CO_2$ as removal continues (Figure 4b). The $CO_2$ benefit was also found to be weaker when CDR was implemented at lower rates. However, unlike for SAT, the $CO_2$ benefit from CDR was found to be higher in the high emission scenario than the lower emissions ones. Thus for any given amount of CDR, the $CO_2$ benefit from CDR is weaker and the SAT benefit is stronger in SSP1 than in SSP5.

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#### 3.2.1 Non-linearity of the TCRR and $CO_2$

The deviation of TCRR from linearity is significant. Previous studies have shown that for geological CDR, in which carbon is permanently removed from the active carbon cycle, the TCRR is linear and only deviates from linearity when the initial climate state in which CDR is applied is not in equilibrium (Jones et al., 2016; Zickfeld et al., 2016, 2021). Furthermore, the TCRR in these studies was not scenario dependent, and instead only depended on the quantity of the cumulative removal. However, the results shown here illustrate that for nature-based CDR, in which the carbon is not permanently removed but instead remains part of the active carbon cycle, the decline in SAT with CDR is non-linear and slows with increasing CDR.

For agricultural CDR and indeed nature-based CDR more generally, more carbon is being stored in natural systems, in this case soil, but this carbon remains part of the active carbon cycle. As a result, some of the removed carbon is returned to the atmosphere via soil respiration, meaning that per unit of CDR there is less of a cooling effect than if the carbon was removed entirely. Thus with more CDR and more respiration, this effect saturates so CDR becomes less effective at reducing SAT because the carbon is more actively cycling. While the TCRR from gross-CDR is non-linear, it is possible that the TCRR from net-CDR is linear, although it was not possible to accurately quantify this for this study.

As for $CO_2$, the deviation from linearity occurs for the same reason, where the removed carbon remains in the active carbon cycle, continuing to respire back in to the atmosphere, so per unit of CDR there is less of a $CO_2$ decline than if the carbon was removed entirely. However, if the only factor affecting $CO_2$ and SAT was that carbon is not being permanently removed, we would expect the SAT benefit to be the same as the $CO_2$ benefit for any given scenario. I.e. if the $CO_2$ benefit is weaker for SSP1 than SSP5, the SAT benefit would be weaker also. This implies the importance of additional effects such as the impacts of CDR on radiative effects, and also the land carbon pools.

#### 3.2.2 SAT and $CO_2$ Dependence on SSP Scenario

The scenario dependence of the TCRR and $CO_2$ benefit in this study is also a significant result, as it differs strongly from previous studies on geological CDR in which the TCRR is linear and path-independent. The SAT benefit of CDR deviates from linearity much more strongly for the higher emissions scenario (SSP5) than the lower emissions scenarios (SSPs 1 and 2). While for $CO_2$ the opposite is true, where the $CO_2$ benefit is closer to being linear for SSP5 than SSP1.

For agricultural CDR, the additional carbon prescribed to be fluxed in to the soil is partitioned in to additional carbon retained in the soil, additional carbon uptake by vegetation, and carbon returned to the atmosphere via soil respiration. The capacity of soil, vegetation, and the atmosphere to store carbon is strongly dependent on the climate, as is the interchange between those pools. Climate change directly and indirectly impacts the biogeochemical processes that determine the strength of the ocean and land carbon sinks. These impacts vary depending on the emissions scenario, thus the fraction of emitted $CO_2$ that remains in the atmosphere is scenario-dependent. This feedback can then amplify or weaken climate change through altering the global radiative balance.

High concentrations of $CO_2$ in the atmosphere cause cumulative ocean $CO_2$ uptake to be reduced due to the weakening of the buffering capacity of the ocean (Katavouta et al., 2018). The warming of the ocean also reduces its ability to dissolve

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$CO_2$, reducing ocean uptake further (Mathesius et al., 2015). Land carbon feedbacks are also strongly scenario dependent. Under high emissions scenarios, heat stress on vegetation, increased stomatal conductance and $CO_2$ fertilization, heat-induced increases in soil respiration, and permafrost carbon feedbacks together act to weaken the strength of the land sink relative to the amount of $CO_2$ emitted (Farquhar and Sharkey, 1982; King et al., 2004; Canadell et al., 2023). Together these mean that in a future with high emissions, the fraction of anthropogenic $CO_2$ that is absorbed by the land and ocean sinks will be significantly smaller than today, thus the cumulative airborne fraction of $CO_2$ is expected to be much larger than that under a low emissions scenario. This will drive a strengthening of the carbon cycle at higher emissions. To a first order, this is reversible, where negative emissions (removal) have a proportionally larger impact on atmospheric carbon storage in a high $CO_2$ climate as shown in Figure 5.

In Figure 5, the bars show the EOC difference between the amount of carbon stored in the CDR minus no-CDR scenarios for each of the land, ocean, and atmosphere pools. The percentages in each bar were computed as $100\times|\Delta C_{stored-i}|/\sum C_{removed}$, where $|\Delta C_{stored}|$ is the absolute value at the EOC of the carbon stored in each pool, i, in the CDR minus the no-CDR scenario; and $\sum C_{removed}$ is the cumulative total of CDR by the EOC. For all SSP and CDR scenarios, the percentage of removed carbon that is retained in the land pool is around 1/3, which will be discussed further in Section 3.3. For all scenarios, there is an increase in land carbon due to CDR, and a corresponding decrease in the amount of carbon stored in the ocean and atmosphere. For SSP1, the decrease in carbon stored in the ocean is around 10% of the total EOC CDR, while for the atmosphere the decrease is 20% of the CDR. For SSP5, the decrease in the ocean pool is proportionally much smaller at only 5%, while the decrease in the atmosphere carbon pool is much higher at 31%. So for a given amount of CDR by the EOC, for example 151 GtC in the high removal scenarios, only 20% of this will be removed from the atmosphere pool in SSP1, but 31% will be removed from the same pool in SSP5. This demonstrates that to a first order, a given amount of CDR will have a proportionally larger impact on the atmosphere carbon pool in a climate with high $CO_2$, even though the land carbon retention is approximately the same. For this reason, the lines for SSP1 in Figure 4b deviate more strongly from linearity than the lines for SSP5, as any given amount of CDR is less effective at inducing $CO_2$ drawdown in a lower emissions scenario.

Since the relationship between changes in atmospheric $CO_2$ and radiative forcing the change produces is logarithmic, at very high $CO_2$ concentrations such as in SSP5, a drop in atmospheric $CO_2$ due to CDR would have very little impact on radiative balance and therefore temperature (Matthews et al., 2009). For SSP1, atmospheric $CO_2$ concentration is lower, thus by the logarithmic relationship, CDR has a larger impact on radiative balance and therefore temperature. For this reason, the SAT benefit from CDR is higher for SSP1 than for SSP5.

#### 3.2.3 SAT and $CO_2$ Dependence on CDR Rate

For both SAT and $CO_2$, the response to cumulative CDR is weaker at lower rates of removal. For example for SSP1, 50 GtC of removal yields a temperature decrease of under 0.04°C when CDR is implemented at a low rate, and 0.05°C for a high rate. $CO_2$ concentration shows a similar pattern, with a decrease of 5 ppm after 50 GtC removed in SSP1, and 10 ppm for the same cumulative removal but at a higher rate. The large difference in SAT and $CO_2$ responses at different CDR rates occurs because the background state of the climate will be very different, if after a given amount of CDR, that CDR was done quickly

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or slowly. For example, 50 GtC of cumulative removal is reached around the EOC for the low removal rate, but before 2055 for the high removal rate. The background state of the climate for all SSPs between 2055 and 2100 are very different. For SSP5, atmospheric $CO_2$ concentration at 2055 is around half of the value at 2100. Therefore, when CDR is implemented at a high rate, any given cumulative removal will be reached sooner and the background state of the climate will be cooler, so the CDR will have a larger impact on radiative balance and thus a larger impact on SAT. For this reason, for the same amount of cumulative removal, the CDR is more effective at reducing SAT if it is implemented at a higher rate as it has a stronger feedback on global radiative balance when atmospheric $CO_2$ is lower.

### 3.3 Land and Soil Carbon Pools

The results above imply that the entire land carbon cycle response to CDR is also strongly dependent on the emissions scenario and rate of removal. In this section we will focus on the land carbon response, and specifically the ability of soil to retain the carbon from the prescribed CDR. Since in these simulations the land surface is not prescribed to change, any impacts of CDR on land carbon should be solely a consequence of carbon cycle dynamics in a changing climate. The changes to the land, and specifically soil carbon pools are driven by the balance between increases in carbon due to direct uptake by plants and soil, and decreases due to indirect impacts of climate change and CDR on vegetation and soil. The balance, and which processes dominate over one another, is scenario-dependent.

As shown in Figure 6a and b, CDR dramatically increases the storage of carbon in the land pool. These increases are slightly scenario and CDR rate dependent (Figure 6b). The changes in the land carbon pool are driven by the changes to vegetation carbon (Figures 6c and d) and soil carbon (Figures 6e and f). The impact of CDR on the land carbon pool is dominated by the prescribed soil carbon flux.

Figures 6c and 6d illustrate the scenario-dependence of the response of vegetation carbon to CDR. As outlined above, in SSP5, vegetation carbon is largely unaffected by CDR since the CDR has a proportionally tiny impact on the massive atmospheric $CO_2$ concentration; thus the impact of CDR on $CO_2$ fertilization is negligible. In SSP1, the impact of CDR on vegetation carbon is dramatic and linear. Since atmospheric $CO_2$ is lower, CDR strongly affects $CO_2$ fertilization, and thus strongly decreases vegetation carbon.

Figures 6e and 6f illustrate the scenario-dependence of the response of soil carbon to CDR. Unsurprisingly, the soil carbon response is primarily dependent on the rate at which CDR is applied. However, it is surprisingly non-linear, illustrating that as CDR continues less carbon is retained in the soil. Furthermore, the soil carbon retention is slightly higher for the high emissions scenario than the lower one.

In theory we may have expected the lower emissions scenario to have better soil carbon retention, but CDR in SSP1 strongly weakens carbon fluxes in to the soil via gross primary productivity (GPP) and leaf litter flux, thereby reducing soil carbon retention. As shown in Figure 7, for SSP1 the impact of CDR on reducing GPP and leaf litter flux is very large and grows with increasing CDR. The impact is substantially larger for higher rates of CDR due to the increased impact on the $CO_2$ fertilization effect. Soil respiration on the other hand only increases slightly in the early stages of CDR due to the flux of carbon in to the soil, then remains constant for increasing amounts of CDR. The initial increase occurs due to increased availability of carbon

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in the soil for microbial respiration, and the subsequent plateau occurs due to the balance of increased available soil carbon increasing respiration and decreased atmospheric temperatures reducing respiration. Therefore the two carbon fluxes in to the soil continually decline with CDR, and the flux out of the soil increases slightly then plateaus. Overall, the strong decrease in carbon flux in to the soil, and minimal increase in carbon flux out of the soil leads to slightly lower soil carbon retention in low emissions scenarios. In contrast for a higher emissions scenario, the impact of CDR on reducing GPP and leaf litter flux is substantially less due to its minimal impact on $CO_2$ fertilization. Soil respiration however increases almost linearly with CDR in SSP5, as soil respiration is not limited by a decrease in temperature like in SSP1. Thus GPP and leaf litter carbon fluxes in to the soil are high and minimally affected by CDR, while there is more flux out of the soil from soil respiration. The net effect is that carbon fluxed in to soil via agricultural CDR is slightly better retained in the soil under high emissions scenarios than low emissions scenarios.

The percentage of carbon that is retained in the soil due to CDR is shown in Figure 8. This was computed as the difference between soil carbon in the CDR minus no-CDR scenario divided by the prescribed carbon input in to the soil. As shown in Figure 8a, the percentage of removed carbon that remains in the soil declines strongly with increasing CDR, and is especially dependent on the rate of CDR. While for any given rate, slightly more soil carbon is retained in the soil for higher emissions scenarios, the more important factor appears to the rate at which the CDR is applied. In all scenarios, soil carbon retention reached around 35% by the EOC, meaning almost two thirds of the carbon fluxed in to soil through CDR cycled back in to the atmosphere. By the EOC, the percentage of soil carbon from CDR that was retained in soil was found to be strongly regionally varying and independent of the rate of CDR and scenario. Figures 8b-d show the regional pattern of the increase in soil carbon by the EOC in the CDR scenario minus the no-CDR scenario divided by regionally varying cumulative carbon input. The spatial panels show the percentage soil retention for the low-removal scenario for SSPs 1, 2, and 5. The spatial pattern is identical for the moderate and high removal scenarios (not shown). The red box shows an example of an area where there is very little CDR applied, due to the presence of present day forests, but a large increase in soil carbon. This is likely due to the climate being overall more favourable due to CDR elsewhere, meaning the increases in soil carbon that would have happened in mid-latitude forests anyway, in the absence of CDR, was improved by the impact of CDR on the global climate even though CDR wasn't applied in that specific location. The blue box shows an area in which the soil carbon retained by the EOC is aligned with the global average. The yellow boxes show locations in which CDR was applied, but very little carbon was retained. This was because of strong soil respiration in these areas (not shown). This illustrates that the ability of global soils to retain any removed carbon in the soil is not spatially uniform, and is instead highly heterogeneous in space. Areas which are predicted to show an increase in stored soil carbon in the absence of CDR, as given in Figure 5.26 of Canadell et al. (2023), showed an even larger increase in soil carbon after CDR even if the CDR was not applied in those areas.

## 4 Conclusions

This study uses simulations of agricultural carbon dioxide removal (CDR) at varying rates to explore the impact on the climate and the global land carbon pools. The simulations were performed using the University of Victoria Earth System Climate

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Model version 2.10. The agricultural CDR was achieved through a prescribed carbon flux from the atmosphere in to soil in agricultural areas. This was prescribed to be time varying, from 0.0 $GtCO_2$ $yr^{-1}$ in 2020, to 3.0, 4.1, or 8.5 $GtCO_2$ $yr^{-1}$ by 2050 based on estimates of low-, moderate-, and high- costs of implementation. These removals were performed under shared socioeconomic pathways 1-1.9, 2-4.5, and 5-8.5.

This study yielded an important finding, that for agricultural CDR, and indeed nature-based CDR more generally, the response of $CO_2$ and surface air temperature to CDR is non-linear, dependent on the emissions scenario in which CDR is implemented, and the rate at which it is applied. We found that realistically-possible agricultural CDR was able to reduce $CO_2$ concentration by 5-19 ppm and global surface air temperature by 0.02-0.10°C by the end of century. The transient climate response to removal was non-linear, with CDR becoming less effective at reducing $CO_2$ and surface air temperature as cumulative removal increased. This was because the carbon removed in nature-based CDR remains part of the active carbon cycle, and thus is not permanently removed. So for a given amount of CDR, some of the carbon removed returns to the atmosphere via soil respiration so the climate benefit is less than if the carbon had been removed entirely.

The response of $CO_2$ and surface air temperature to agricultural CDR strongly depended on the scenario in which it was applied. In low emissions scenarios, CDR was less effective at reducing atmospheric $CO_2$ for a given amount of CDR than the same amount of CDR in a high emissions scenario. On the other hand, in low emissions scenarios CDR was more effective at reducing the surface air temperature than it was in a high emissions scenario. The larger temperature response in low emissions scenarios was due to the logarithmic nature of the relationship between atmospheric $CO_2$ concentration and its impact on radiative balance, where at low atmospheric $CO_2$, CDR has a proportionally larger impact than for a high emissions scenario. CDR was substantially more effective at reducing surface air temperature when it was implemented at a more rapid rate.

The impact of CDR on land and soil carbon was determined by the balance between increases in carbon due to uptake by plants and soil, and decreases due to indirect impacts of climate change, such as soil respiration. In low emissions scenarios, there was a sharp decline in gross primary productivity and leaf litter flux due to the $CO_2$ fertilization effect, and only slight increase in soil respiration due to more soil carbon availability. The net result was slightly lower soil carbon retention than for the high emissions scenario, in which primary productivity was largely unaffected by CDR due to the logarithmic relationship between atmospheric $CO_2$ changes and the $CO_2$ fertilization effect, and soil respiration increased due to soil carbon availability and global temperature increase. Thus for low emissions scenarios, the decrease in primary productivity due to CDR is important for setting the retention of removed carbon in the soil, but for high emissions scenarios respiration was the dominant factor affected by CDR. The soil carbon was found to be retained at a higher fraction for longer if the CDR rate was higher.

Further study on this topic will explore the climate impact from agricultural CDR where a portion of the carbon removed enters the inactive carbon cycle through biochar pyrogenic carbon capture. Furthermore, we will explore the impact of land management practices such as tilling, which would undoubtedly affect these results through routine soil disturbances.

*Code and data availability.* Model output data and code has been uploaded to the Canadian Federal Research Data Repository. https://doi.org/13e1b9db-0d94-4197-b9e0-bee4c5ab9157

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*Competing interests.* The authors declare that no competing interests are present.

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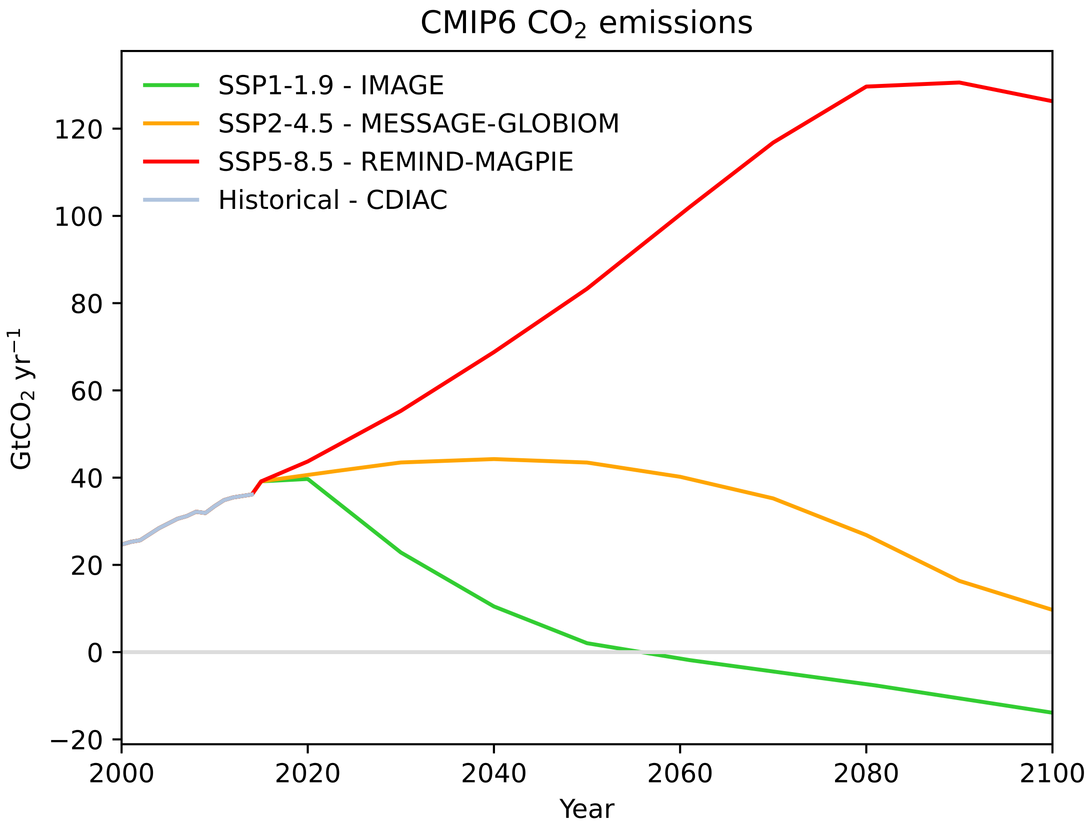


**Figure 1.** The three Shared Socioeconomic Pathways (SSPs) used in this study and historical $CO_2$ emissions. The SSP data is from 2015-2100Meinshausen et al. (2020). SSP1-1.9 is from the IMAGE integrated assessment model, SSP2-4.5 from MESSAGE-GLOBIOM, and SSP5-8.5 from REMIND-MAGPIE. Historical emissions were taken from the Carbon Dioxide Information Analysis Center.

**Figures**

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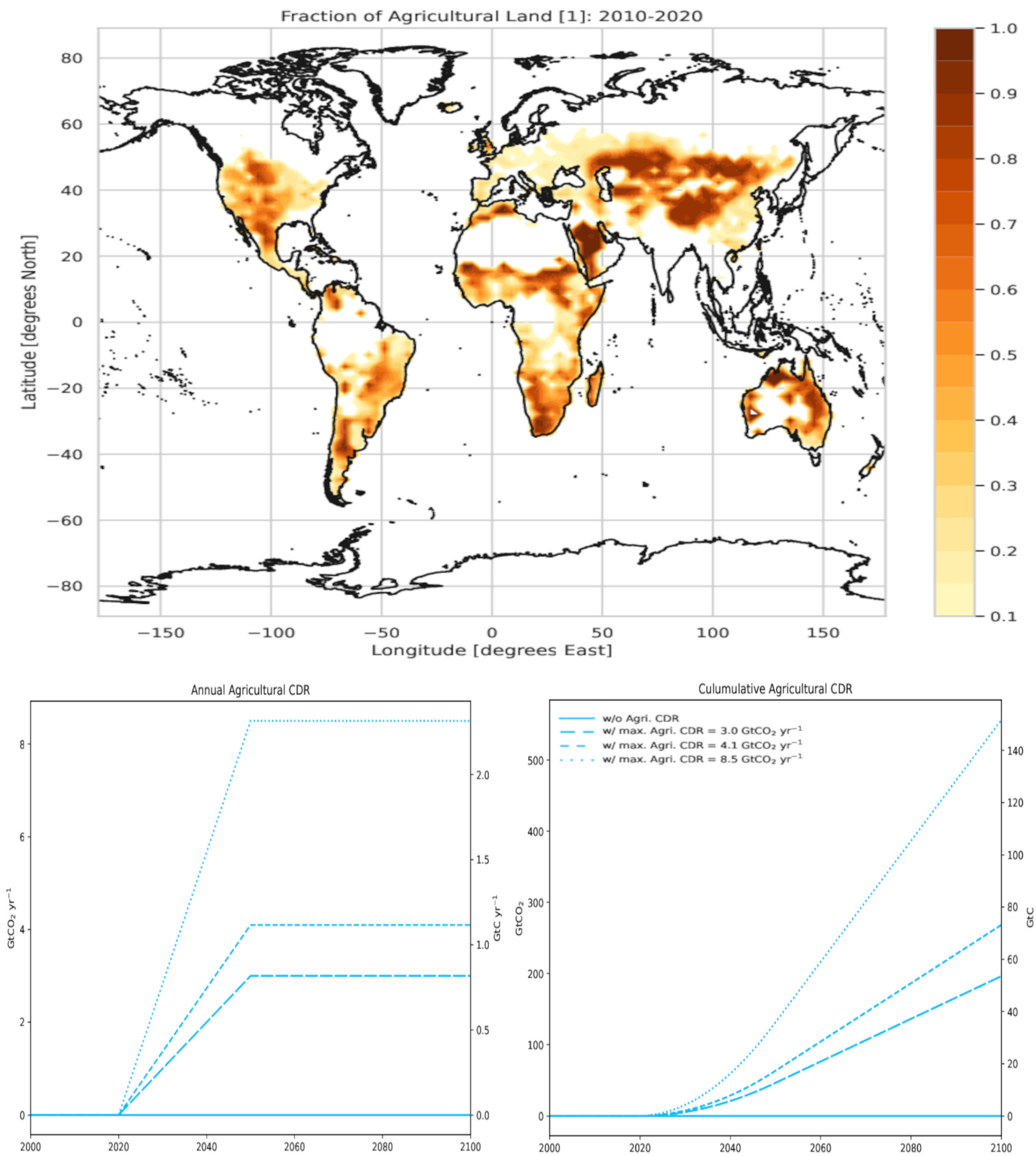


**Figure 2.** The upper plot shows the agricultural area fraction between 2010-2020, which was used to prescribe the locations of the CDR and amount of CDR per grid square. The lower plots show the annual and cumulative prescribed global agricultural CDR for the low removal (3.0 $GtCO_2\ yr^{-1}$ by 2050), moderate removal (4.5 $GtCO_2\ yr^{-1}$), and high removal scenarios (8.5 $GtCO_2\ yr^{-1}$). Cumulative total removal by 2100 is 196.5 $GtCO_2$, 268.6 $GtCO_2$, and 556.8 $GtCO_2$ in the low-, moderate-, and high-removal scenarios respectively. The long-dashed, short-dashed, and dotted lines will hereafter be used to represent the low-, moderate-, and high-removal scenarios respectively.

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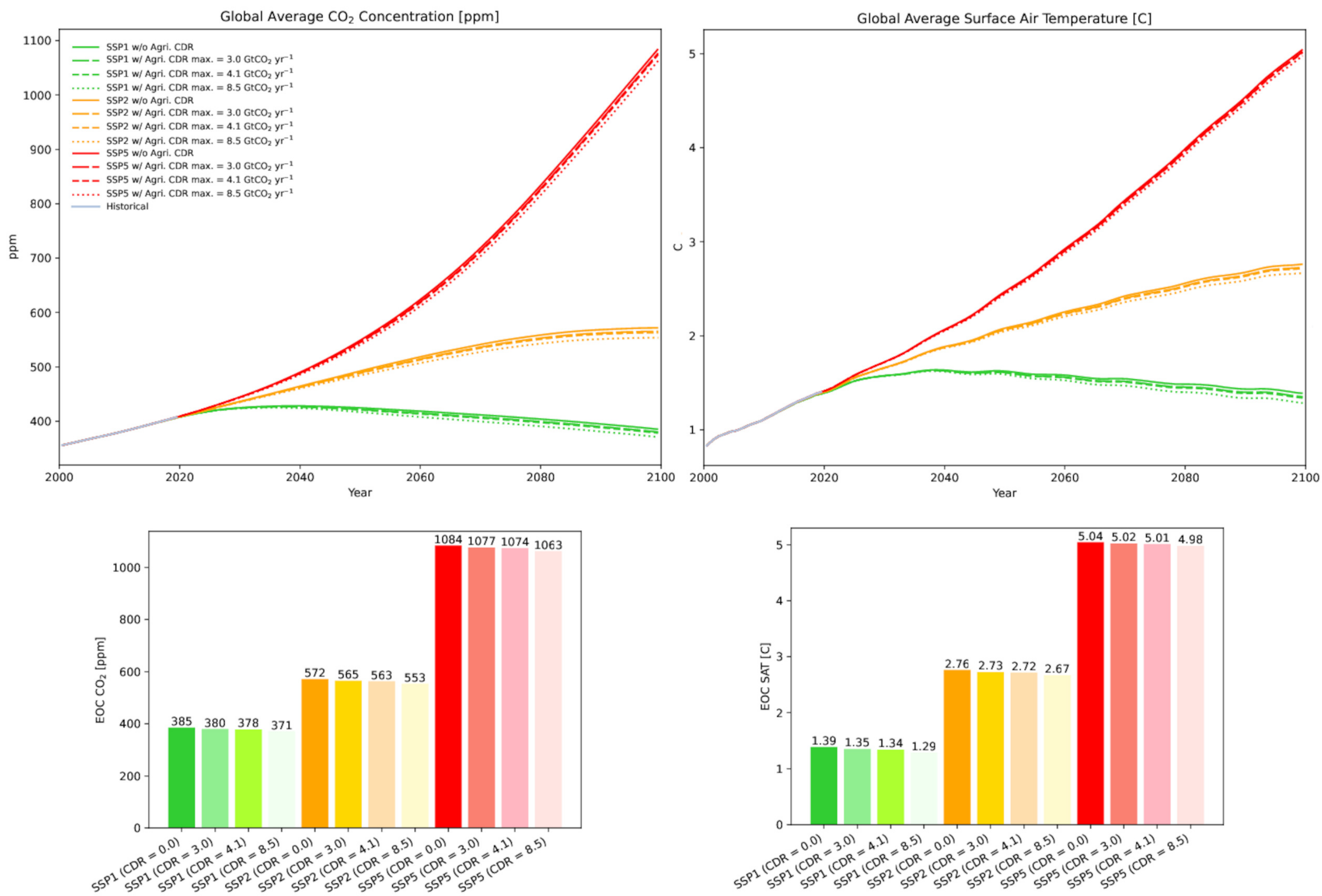


**Figure 3.** The upper line plots show the $CO_2$ concentration (left) and surface air temperature (right) with time. The lower bar charts show the End-of-century (EOC) $CO_2$ concentrations and surface air temperature in each simulation.

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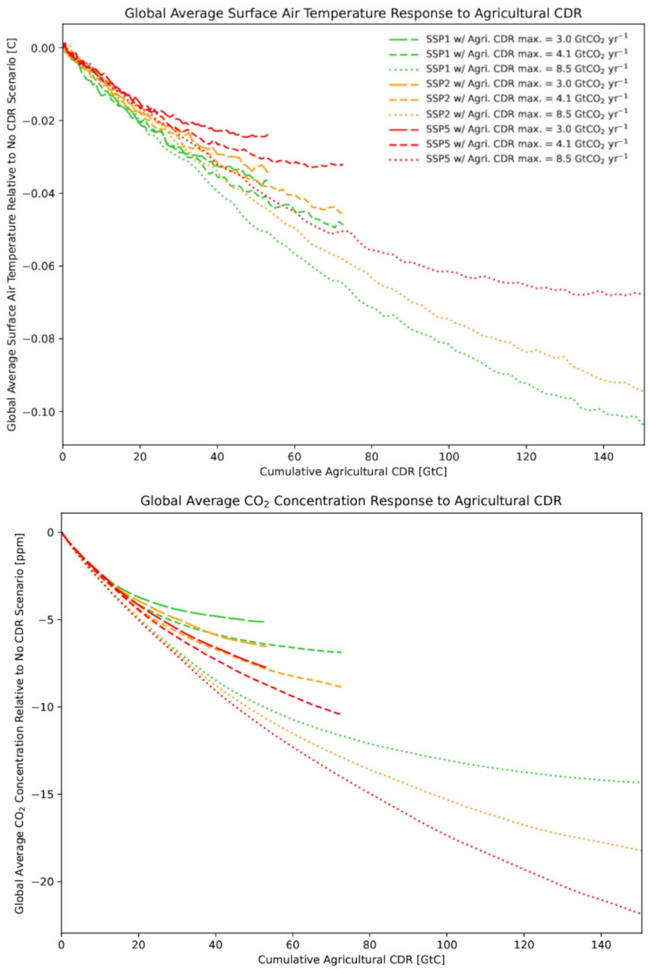


**Figure 4.** Transient Climate Response to Removal Plots. The uppermost plot (a) shows the global average surface air temperature response (CDR scenario minus no-CDR scenario) to cumulative removal. The bottom plot (b) shows the global $CO_2$ concentration response to cumulative removal.

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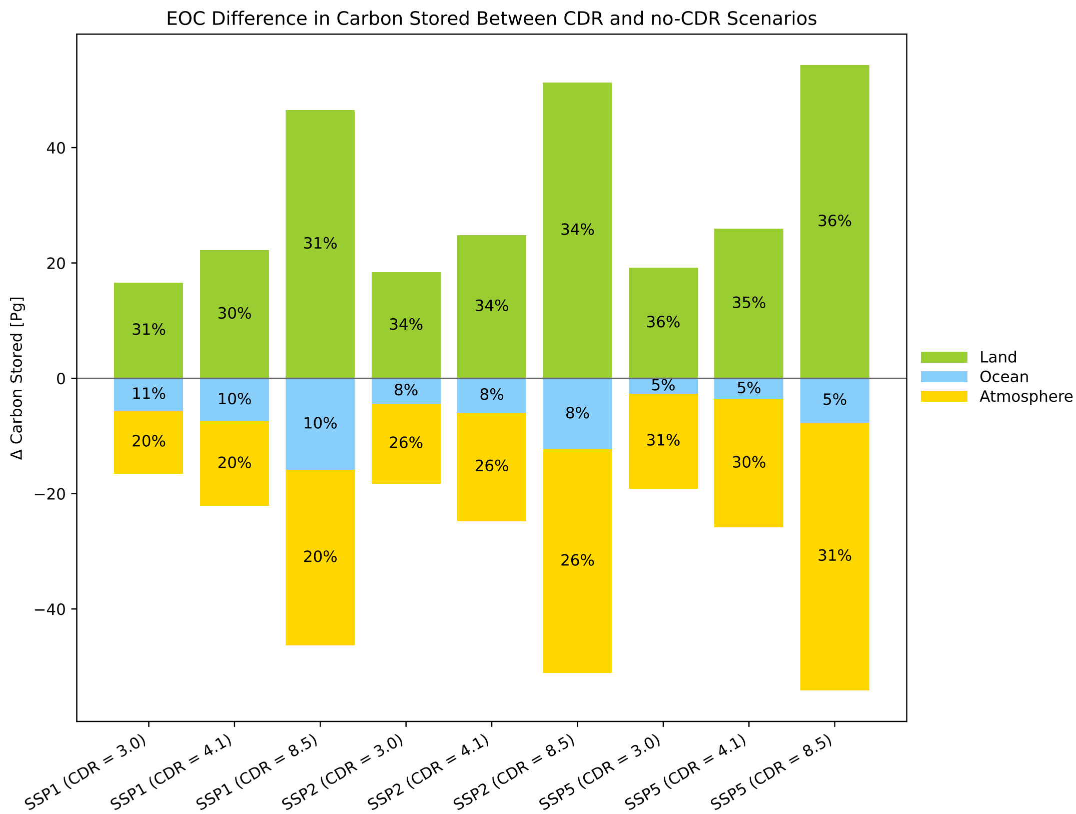


**Figure 5.** The difference at the end-of-century between the amount of carbon stored in the CDR minus no-CDR scenario for each of the land, ocean, and atmosphere pools. The percentages in each bar show the absolute value of the proportion of removed carbon retained in each pool.

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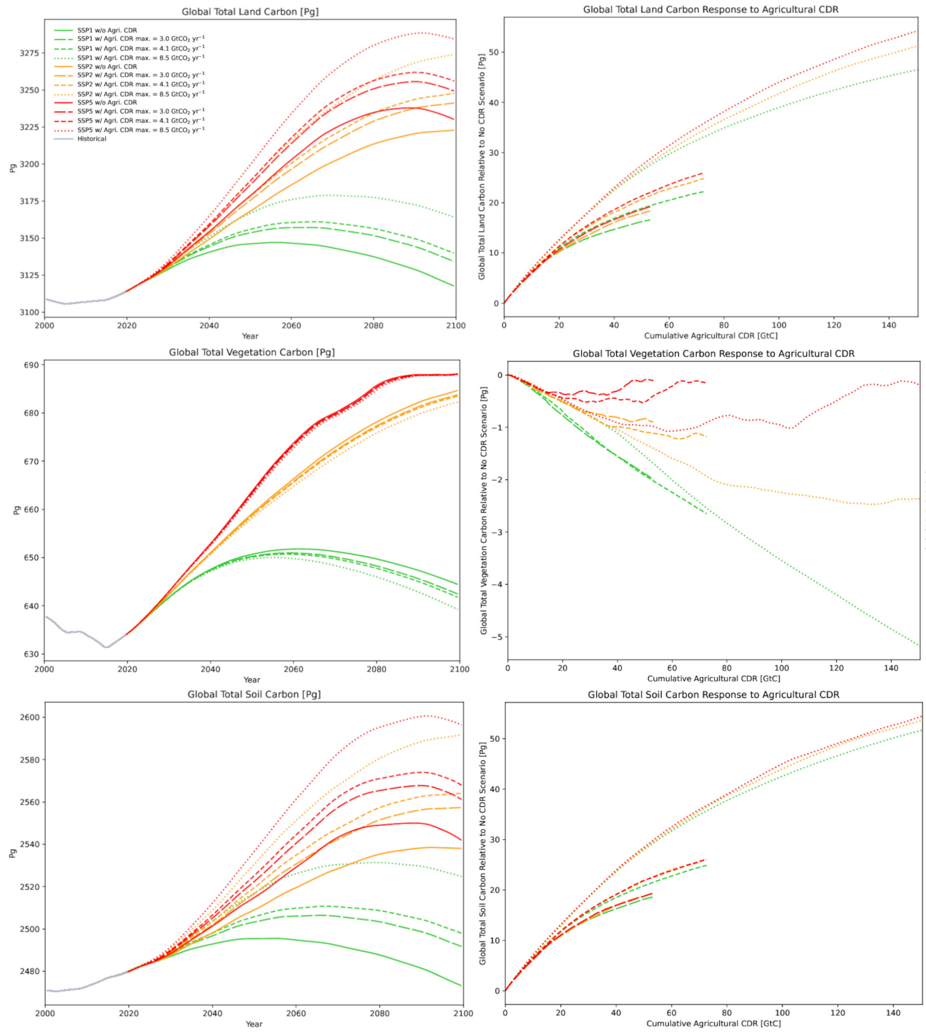


**Figure 6.** The global total land carbon pool and its soil and vegetation components. The left column shows the carbon storage totals with time. The right column shows the difference in carbon storage between the CDR and no-CDR scenarios against cumulative removal.

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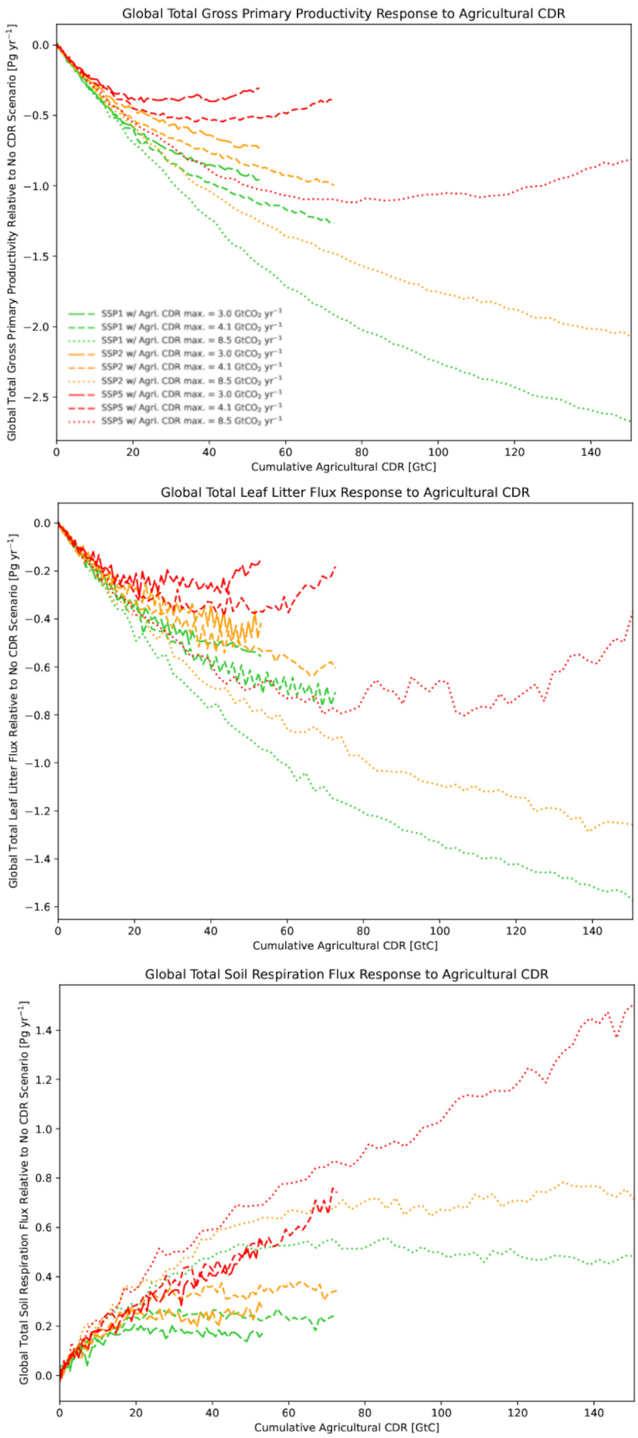


**Figure 7.** The components of soil carbon flux. The plots show the fluxes in the CDR scenarios minus the no-CDR scenarios against cumulative removal for (a) gross primary productivity (GPP), (b) soil respiration, and (c) leaf litter.

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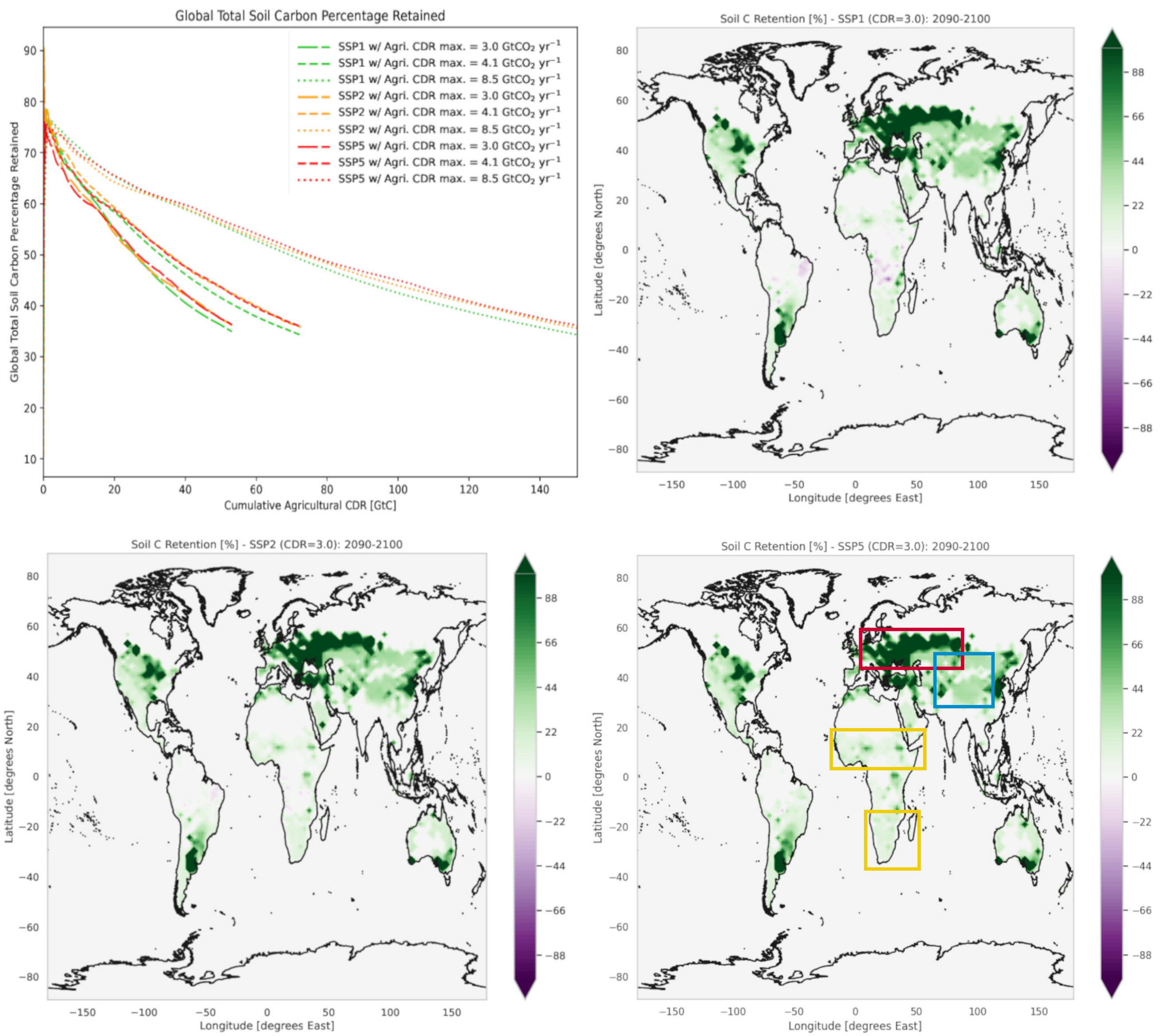


**Figure 8.** The percentage of carbon retained in the soil as (a) a function of time, and (b-d) a function of space averaged for the period 2090-2100 for SSP's 1, 2, and 5 for the low removal scenario. The spatial pattern of the plots in (b-d) is identical to that for the moderate- and high- removal scenarios (not shown). The red box shows an example of a region where there is little applied CDR, but very high C retention in soil; the blue box is an example of a region where the percentage of soil carbon retained is around the global average of 30%; the yellow boxes show examples of regions where CDR is prescribed to be strong but little soil C is retained. The regional variability of CDR can be found in Figure 2.