Title: Cost of cooling: The value of reversible carbon storage in a zero-emissions world

Authors: Allegra Mayer[1], Jerome Dumortier[2], Zeke Hausfather[3], Jennifer Pett-Ridge[1,4,5], Eric Slessarev[6,7]

Affiliations:

[1] Lawrence Livermore National Laboratory, Physical Life Sciences Division, Livermore, CA, USA

[2] Indiana University Indianapolis, O'Neill School of Public and Environmental Affairs, Indianapolis, IN, USA

[3] Stripe Inc., South San Francisco, CA USA

[4] Life and Environmental Sciences Department, University of California, Merced, CA, USA

[5] Innovative Genomics Institute, University of California, Berkeley, CA USA

[6] Yale University, Department of Ecology and Evolutionary Biology, New Haven, CT, USA

[7] Yale University, Yale Center for Natural Carbon Capture, New Haven, CT, USA

Abstract

Atmospheric carbon dioxide removal (CDR) is required to stabilize global temperature and can be achieved via ecosystem (e.g., soil and forest management) and geological (e.g., direct air capture) carbon storage. Ecosystem strategies are scalable and cost-effective but reversible, making their long-term impact on climate mitigation uncertain. Geological storage is permanent but currently expensive. This paper examines trade-offs between these approaches, focusing on timing, contract structures, and cost. Using agricultural soil management—specifically cover crops—as a case study, we simulated reversible soil carbon accrual for a range of CDR contract structures using a simplified biogeochemical model. We then quantified the resulting impact on atmospheric carbon and global temperature using a climate model emulator. We find that maintaining a patchwork of temporary CDR projects by replacing lapsed projects with new projects can reduce warming and that the magnitude of this cooling effect depends on how successfully the patchwork is maintained. Long term maintenance of temporary CDR projects requires institutional stability that cannot be guaranteed over multiple decades. Consequently, effective CDR ultimately requires replacing temporary projects with permanent projects. To address this problem, we modeled the cost of replacing temporary ecosystem CDR with geologic CDR. We found that using temporary CDR as a bridge to permanent CDR is potentially more cost effective as a global cooling strategy than perpetual maintenance of temporary CDR or an immediate transition to permanent CDR. However, we emphasize that institutional commitments to maintain temporary CDR projects are reversible. Reliance on temporary CDR as a bridge to permanent CDR therefore carries an unknown amount of risk and will only function if efforts to maintain temporary CDR are robust.

Introduction

Carbon dioxide removal (CDR) will be necessary to limit warming to meet climate targets in tandem with simultaneous decarbonization (Calvin *et al* 2023). CDR pathways that yield permanent storage are currently expensive, energetically demanding, and are not yet scalable (e.g., biomass with carbon removal and storage, direct air capture with geologic storage, enhanced rock weathering, ocean alkalinity enhancement). By contrast, ecosystem-based CDR pathways (e.g., forest and soil carbon) provide many environmental benefits and are immediately scalable, low-energy, and inexpensive but do not provide permanent storage because plant biomass and soil organic matter can burn or decompose and return to the atmosphere. Thus, it is difficult to evaluate how ecosystem carbon storage might contribute to climate change mitigation.

When CO_2 is removed from the atmosphere, the climate forcing response will be the same no matter where the removed CO_2 is stored. However, the duration of storage and its relation to timing of decarbonization efforts does affect climate forcing. Carbon that is stored temporarily in ecosystems and then re-emitted to the atmosphere prior to reaching net-zero emissions and peak warming has virtually no long-term climate mitigation effect when compared to the same amount of CO_2 in permanent storage starting at the same time (Matthews *et al* 2022, Brunner *et al* 2024). On the other hand, temporary storage can reduce peak global warming when combined with strong fossil fuel emissions reductions, or delay peak global warming when combined with medium emissions reductions (Matthews *et al* 2022, Leifeld and Keel 2022). The effectiveness of temporary storage depends on its duration and timing. Temporary storage will be most effective at mitigating climate change if it is initiated as early as possible and maintained until after peak warming (Jorgensen *et al* 2015), which itself depends on future emissions policy and actions. If temporary storage is reversed prior to a climate stabilization, the climate forcing response could actually be worse in the short-term than the case without any temporary storage (Jorgensen *et al* 2015). This analysis explores how different mechanisms for implementing and maintaining temporary CDR affect its durability and effects on global temperature.

Ecosystem CDR projects are typically commissioned by institutions (e.g., governments, private companies) but are implemented by individual landowners. Institutions incentivize CDR by establishing contracts that offer compensation to landowners to change management practice and enhance carbon storage. Century long commitments to ecosystem carbon storage may be desirable from a climate perspective but are likely untenable for individual landowners. Shorter contracts increase participation due to greater flexibility. While shorter temporary storage projects are technically less effective at reducing warming effects at the scale of individual land parcels, a patchwork of contracts across space and time can achieve the same effects as one large-scale project (Wise *et al* 2019). Stacking shorter-term ecosystem carbon storage contracts over time, space, or both, may in theory be just as effective as a single continuous commitment, provided that expired contracts are replaced. Although stacking ecosystem CDR projects theoretically enables continuous carbon storage despite release at the level of individual land parcels, it depends on the institution managing the aggregated projects to uphold its commitment and maintain financial stability. Horizontal stacking (i.e., stacking over time) also rests on the assumption that the release of ecosystem carbon occurs at relatively small scales, and that counterfactual storage of carbon in these systems would not happen in the absence of anthropogenic interventions (e.g., natural vegetative growth in the case of reforestation projects). Replacing carbon storage contracts may become impossible if climate change or large-scale economic shocks reduce the overall capacity of the ecosystem to remove and store carbon. In this sense horizontal stacking does not generate permanent ecosystem C storage; rather, it guards against local release of carbon storage.

Technological approaches that more permanently remove atmospheric CO_2 include direct air capture with carbon storage (DACS), biomass with carbon removal and storage (BiCRS), enhanced rock weathering (ERW), and ocean alkalinity enhancement (OAE), among others. They durably store CO_2 in geological storage or in stable carbonate or bicarbonate mineral forms at the surface or in the oceans (Smith *et al* 2024). The permanence and reversal risks of these different storage pathways differ, but all are expected to result in more than 10,000 years of CO_2 storage (Ibid). For the purposes of this analysis, we use DACS as a proxy for different high durability CDR pathways as it has a large potential, though other approaches will likely represent a larger share of near-term permanent CDR deployment (Fuhrman *et al* 2023).

While horizontal stacking of temporary carbon storage can affect the trajectory of climate change, a more secure CDR approach is to prioritize permanent storage pathways that have near zero probability of reversal over geologic timescales. Permanent CDR is relatively nascent today, with relatively few tons delivered from projects to-date (Smith *et al* 2024). However, the sector is rapidly expanding, and is likely to reach a scale of tens of millions of tons per year by 2030

(Guzzardi *et al* 2024). Current costs of permanent CDR generally exceed \$200 per metric ton of CO_2-equivalent (Mg^{-1} CO_2-e), with some pathways (e.g., DACS) above \$500 Mg^{-1} CO_2-e (Agbo *et al* 2024, Guzzardi *et al* 2024). Although these costs are expected to decrease over time due to learning through larger scale deployments, they will likely remain over \$100 Mg^{-1} CO_2-e for the next 50 years (LLNL 2023, Guzzardi *et al* 2024). Scaling depends on investments, regulatory constraints for permitting, technological development, and cultural, social, and environmental justice constraints around projects in vulnerable areas. From an investment perspective, we frame permanent CDR and storage as "buying" carbon storage as an expensive but one-time investment, in contrast to "renting" temporary storage via horizontal stacking, which is less expensive but must be continuously invested in over time (Herzog *et al* 2003, Marland *et al* 2001).

Comparing temporary and permanent carbon storage is fraught with challenges because the effect of temporary carbon storage on the climate over the coming century depends on the storage duration, which is uncertain. Ton-year accounting and the like-for-like principle have been proposed as solutions to valuing shorter duration carbon storage (Schenuit *et al* 2023, Moura Costa and Wilson 2000, Fearnside *et al* 2000, Allen *et al* 2022). These frameworks do not quantitatively account for risks and benefits of competition between temporary carbon storage and permanent storage pathways over time. This analysis evaluates (1) the climate forcing and cost trade-offs of temporary ecosystem carbon storage in a horizontal stacking framework and (2) horizontal stacking of temporary storage, buying permanent storage, or a combination of the two. Our analysis thus aims to identify how and to what extent temporary carbon storage can contribute to reducing climate warming in a net zero-emissions world. To compare these scenarios, we integrate three models representing (1) the dynamic biogeochemical impacts across a spatial patchwork of ecosystem CDR projects that are maintained with varying degrees of success, (2) the biophysical climate forcing (temperature) effects, and (3) cost. We then analyze a range of trajectories for transitioning from "renting" temporary CDR storage projects implemented immediately and stacked horizontally over time and space to "buying" permanent geologic-scale carbon storage within this century.

We use this modeling framework to explore two main hypotheses. First, we assess the climate and cost tradeoffs associated with implementing new temporary CDR projects (with faster accrual rates) versus maintaining CDR projects for longer (delaying release). We explore the efficacy of CDR across a range of contract renewal rates. The renewal rate summarizes the success of ecosystem CDR in maintaining CDR projects over time and might respond to a range of potential factors (e.g., economic shocks, government policy reversals, changes in corporate CDR commitments). We hypothesize that maximizing negative radiative forcing per dollar spent over a 50- to a 100-year period requires maintenance of CDR projects that are no longer accruing carbon, but that maintenance of some CDR projects can lapse without repercussion (i.e. increasing warming) provided that lost CDR is replaced with new CDR. Second, we quantify the magnitude and length of the contribution of continuously "renting" temporary projects until eventually "buying" permanent storage. Specifically, we model a system in which landowners receive an incentive payment to accumulate carbon in the soil through a change in management practice. Prior to the expiration of the incentive, the contract can either be renewed to keep the carbon in the soil or terminated with carbon lost after reversion of management partially or fully replaced with immediate permanent CDR. We hypothesize that as the cost of permanent CDR declines, the proportion of carbon stored in permanent CDR projects should be able to financially compete with temporary projects in the long-term, suggesting the use of temporary projects as a bridging mechanism, rather than a final storage solution.

Methods

First, we implemented a one-pool soil carbon model to track annual carbon sequestration and release in response to cover cropping, a soil management practice that is thought to yield CDR. We chose cover cropping because it is not widely practiced and hence adoption is likely to be additional. Cover cropping also does not directly compete with commodity crop production or require import of exogenous biomass (Pett-Ridge *et al* 2023). Next, we combined the soil model with a land-use model to track carbon sequestration and release across space as land area shifts in and out of temporary carbon sequestration projects. We simulated different contract renewal rates assuming an overall project start in 2025. Depending on the scenario, not all carbon released was added to the atmosphere; instead, a fraction of released carbon could be stored in permanent CDR projects based on the expansion of DACS technology. We fed the carbon fluxes from the land-use model into the Finite Amplitude Impulse Response (FaIR 1.6.4) model to calculate the associated effects on global temperature (Smith *et al* 2018, Millar *et al* 2017, Nicholls *et al* 2020). Lastly, we used an economic model to attribute cost to the various CDR pathways and temperature effects.

Soil Organic Carbon Model

We simulated soil carbon storage due to cover cropping with a linear one-pool soil organic carbon (SOC) model. We acknowledge that the effect of cover crops on SOC remains debated (Chaplot and Smith 2023, Jian *et al* 2020, Tautges *et al* 2019, McClelland *et al* 2021), but for the purposes of this analysis we assumed that cover crops increase SOC stocks. We define the management practice as either implementing cover crops or managing land with the business-as-usual practice (i.e., no cover crops). The rate of change in SOC was governed by a single differential equation (Caruso *et al* 2018):

$$dC_{soil}/dt = nI - kC_{soil} \quad (1)$$

Where C_{soil} is the soil carbon stock (Mg C ha^{-1}), I is the rate of carbon input (Mg C ha^{-1} y^{-1}) *n* is the fraction of carbon input that enters the soil (unitless), and k is a first order decay constant (y^{-1}). SOC stocks were calculated on an annual timestep using the integral of Equation (1):

$$C_{soil}(t) = \frac{n}{k}I - \left(\frac{n}{k}I - C_0\right)e^{-k(t-t_0)} \quad (2)$$

Where C_0 is the SOC stock (Mg C ha^{-1}) at time t_0. We parametrized this equation so that the steady state SOC stock without cover cropping (defined as C_{bau}) would be 53 Mg C ha^{-1}, which corresponds to the mean organic carbon stock in the top 20 cm of cropland soil in US croplands (Zhang *et al* 2020). The decay constant *k* was parameterized as 0.05 y^{-1}, based on published values for grass planted on cropland soil (Johnston *et al* 2009, Caruso *et al* 2018). The I and *n* parameters were constrained by the fact that at steady state C_{soil} equals I*n/k. Assuming a value of 0.5 for n and considering our assumption that C_{bau} = 53 Mg C ha^{-1} at steady state, I in the business-as-usual scenario (I_{bau}) equaled 5.3 Mg C ha^{-1} y^{-1}. This value is on the high end annual carbon inputs in midwestern corn-soybean systems (Poffenbarger *et al* 2017). We increased the value of I by 0.6 Mg C ha^{-1} yr^{-1} under cover cropping so that the change in carbon stocks would be approximately 0.3 Mg C ha^{-1} y^{-1} for the first five years after initiating the practice (I_{cc} = 5.9 Mg C ha^{-1} y^{-1}). An increase in SOC of 0.3 Mg C ha^{-1} y^{-1} over this timeframe is consistent with mean estimates of soil carbon accrual from implementing cover crops on annual croplands (Blanco-Canqui 2022). We note that the 0.6 Mg C ha^{-1} y^{-1} increase in inputs with cover crops is comparable to the mean root carbon inputs from cover crops in the United States (Blanco-Canqui *et al* 2020), but is less than the expected mean biomass inputs when accounting for both above- and below-ground cover crop biomass (~ 2 Mg C ha^{-1} yr^{-1}) (Ruis *et al* 2019, Blanco-Canqui *et al* 2020). This model accounts for the variable rate of soil carbon accrual over time, where a patch that has been contracted three times in a row accrues at a slower rate than a patch of land contracted for the first time **(Figure 1**). We note that these parameters could be adjusted for any ecological storage pathway that approaches equilibrium.

The SOC stored per unit area over time (C_{soil}, Mg ha^{-1}) was obtained by constructing and parametrizing a piece-wise function from Equation 2:

$$C_{soil} = \begin{cases} \frac{n}{k} I_{bau} = C_{bau} & if\ t \leq t_e \\ \frac{n}{k} I_{cc} - \left(\frac{n}{k} I_{cc} - \frac{n}{k} I_{bau}\right) e^{-k(t - t_e)} & if\ t_e < t \leq t_u \\ \frac{n}{k} I_{bau} - \left(\frac{n}{k} I_{bau} - C_u\right) e^{-k(t - t_e)} & if\ t > t_u \end{cases} \quad (3)$$

Where t_e is the time when the patch enrolls in cover cropping and t_u is the time when it unenrolls. The quantity C_u was defined as the SOC stock when the patch reverts from cover cropping to business-as-usual management and was obtained by solving Equation 2 at time = t_u:

$$C_u = \frac{n}{k} I_{cc} - \left(\frac{n}{k} I_{cc} - \frac{n}{k} I_{bau}\right) e^{-k(t_u - t_e)} \quad (4)$$

Net SOC storage (C_{store}, Mg ha^{-1}) was then calculated by subtracting C_{bau} from the solution to Equation 3.

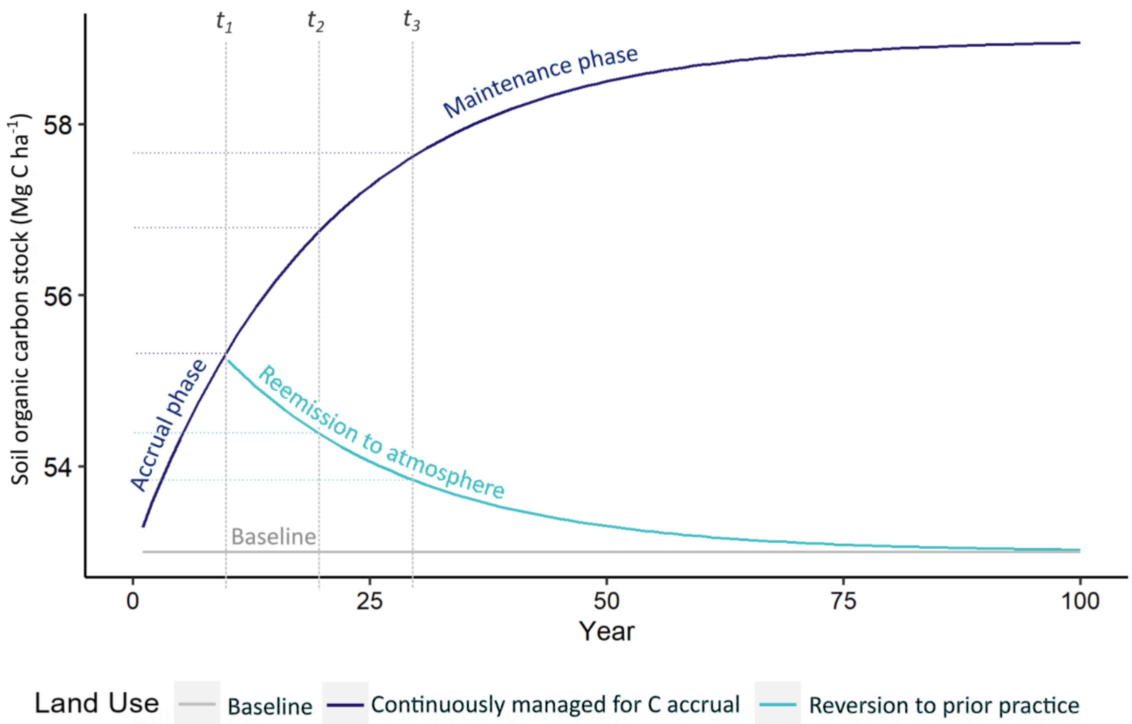

Figure 1: Simulated soil organic carbon stock over time using a one-pool model given (1) a steady state baseline (gray line) of 53 Mg C ha^{-1}, (2) land under continuous CDR management practice such as cover cropping (purple line), and (3) land that had been under a cover crop regime for ten years but returned to original management practice with baseline inputs (blue line). Soil CDR contracts that are renewed through time t_2, t_3, or later have diminishing carbon accrual returns over time and contracted projects reach the maintenance phase of carbon accrual rather than the accrual phase. Soil carbon release from land reverted to previous practice (blue line) follows the same assumptions for decomposition as in the other two cases, but with initial carbon as the value of soil carbon stock whenever the contract ended, and carbon inputs shifting back to the original management practice. Importantly, though soil carbon is being released after reversion to prior practice, total carbon stock remains higher than baseline for decades following reversion under these conditions.

Patchwork Land-Use Model

We developed a land use model to track carbon accrual and loss as patches of land shift into and out of temporary carbon storage over time. We defined a “patch” as an area of land that shares a common management history: in each patch cover cropping is implemented and then lapses at the same time. To construct the patchwork, we simulated a range of possible management contract outcomes with renewal rates of 0%, 25%, 50%, 75%, and 100% as well as contract lengths of 5–20 years in increments of 5 years. We report results for 10 year contracts in the main text, and include results from all contract lengths in the supplemental information. We used a total land area of 91 million hectares which is equivalent to the area planted in corn, soybeans, or wheat in the USA in 2022 (Nseir and Honig 2022). We limited total land under soil carbon accrual practices (A_t) to 25% (i.e., 22.75 million ha) at any point in time, which is slightly higher than current enrollment rates for incentivized cropland conservation programs in the USA (e.g. Environmental Quality Incentive Program) (Newton 2019). Land not subject to contract renewal and reverting to the baseline practice at the end of the contract was replaced with the same amount of land being enrolled in the carbon-removal practice. Replacement occurred until each unit of land has been under contract at least once. For example, for the contract length of ten years and the renewal rate of 25%, 22.75 million hectares were put under new cover cropping contracts in 2025, whereas 17.1 million hectares were put under new contracts and 5.7 hectares were renewed in the years 2030, 2035, 2040, 2045. The land area in each patch (A_p) is time invariant because each patch is defined in terms of a unique combination of t_e and t_u. in addition to the renewal rate (r) and the contract length (l):

$$A_p = \begin{cases} A_t(1-r)r^{m-1} & if\ t_e = 0 \\ A_t(1-r)^2 r^{m-1} & if\ t_e > 0 \end{cases} \qquad (5)$$

Where the variable m is the number of contract periods that had elapsed when the patch was unenrolled:

$$m = \frac{(t_u - t_e)}{l} \qquad (6)$$

We then calculated the total amount of C stored in the patch over time (C_{patch}, Mg C) by multiplying A_p by C_{store}. The patchwork was defined for all combinations of t_e and t_u constrained by the contract length, with the constraint that t_e could not be greater than the simulation year in which all available land had been under contract once. We then summed C_{patch} across all patches to obtain total CDR over time.

Transition from temporary to permanent CDR

In the patchwork land-use model, carbon was released back into the atmosphere when contracts are not renewed or replaced. We modeled scenarios in which net carbon released is permanently removed through DACS at the prevailing cost in the year of release. Since there is uncertainty about how quickly DACS will scale over time, we evaluated temporary ("rent") to permanent ("buy") transition pathways to understand the degree to which temporary carbon removal and storage might bridge a gap to permanent carbon storage. We assumed a logistic growth curve reaching 95% removal of carbon emitted by 2050 and 2075, which we labelled Logistic Growth (2050) and Logistic Growth (2075), respectively. To compare the effects both in terms of temperature and cost, we also simulated "rent only" and "buy only" scenarios. The "rent only" scenarios assumed no permanent storage and the "buy only" scenarios assumed immediate permanent storage via DACS, with a net CDR trajectory that replicates the carbon removal achieved from the different ecological CDRs based on renewal rate. We note that with the development of new CDR technologies, more CDR will be available by 2050 than what is modeled in this study (Pett-Ridge *et al* 2023, Fajardy *et al* 2019, Minx *et al* 2018). The DACS diffusion curves used in this analysis are available in the Supplemental Information (**Figure S1**).

Translation to climate warming reduction

We translated spatially cumulative carbon fluxes from the patchwork land-use model to climate forcing effects using a climate model emulator, the *FaIR model* (Smith *et al* 2018, Millar *et al* 2017). Specifically, we added rates of soil carbon uptake or emission in units of Mg C y^{-1} to global greenhouse gas emissions scenarios for two Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP): (1) SSP1-2.6, a scenario with global cooperation and major emissions reductions, and (2) SSP 2-4.5, which simulates moderate global emissions reductions (Riahi *et al* 2017). We present results using a baseline of SSP1-2.6, as the major shift to permanent storage simulated in this research is most consistent with this land-use and emissions storyline. The *FaIR model* (Smith *et al* 2018) calculates the global impact of carbon fluxes on radiative forcing and mean global temperature. For each contract renewal rate, the change in carbon fluxes and associated change in climate forcing were compared to climate forcing outcomes assuming only the baseline emissions (e.g., SSP1-2.6), and we report relative change in warming. Results for a baseline of SSP2-4.5 and for contract lengths from 5 to 20 years are available in the supplemental information (**Figures S5 & S6**).

Economic Aspects

There are three cost components associated with the patchwork land-use model: the costs of temporary storage, cost of permanent storage, and the discount rate. Regarding the cost of temporary soil storage, we assumed a practice-based as opposed to a results-based payment policy. That is, landowners are compensated per hectare of land enrolled in the practice. A results-based policy would compensate landowners based on the carbon sequestered on an annual basis but since the sequestration rate is decreasing over time (**Figure 1**), the payment received would approach zero in the long-run making it unlikely for a landowner to renew a contract. The disadvantage of practice-based payments is that landowners get compensated for the practice (even in the very long run) even if no carbon is accumulated in the soil.

We considered three carbon payment paths, which we labeled Low C Value, Medium C Value, and High C Value (**Figure S3**). The growth rate for each path was set to 1% and the starting values in 2025 were \$50, \$125, and \$200 per metric ton CO_2 for low, medium, and high price paths, respectively. For the three price paths, we assumed that the maximum value was \$250, \$500, and \$1000 per metric ton CO_2 for the low, medium, and high value, respectively. If contracts renewed, the payment started with the value prevailing in the renewal year. The price was measured in USD per hectare of land enrolled in cover cropping. As with other components of our analysis, there is substantial uncertainty regarding the payment to landowners for temporary carbon removal and storage, which is reflected in our carbon value paths. The resulting carbon price trajectories are in line with published values (Strefler *et al* 2021).

The future cost of DACS is highly uncertain, with current cost estimates ranging from \$600–\$1000 Mg^{-1} CO_2-e (McQueen, et al., 2021). A similar issue arises with projecting the cost in the long run. In this analysis, we assumed three DACS cost trajectories consistent with estimates starting at \$500, \$750, and \$1000 Mg^{-1} CO_2-e in 2025 and declining to \$150, \$250, and \$500 Mg^{-1} CO_2-e in the long term (**Figure S1b**). Those values should be comparable to the carbon payments per hectare that are increasing over time.

Note that unlike in Herzog et al. (2003), there is the possibility that the carbon price grows at a different rate than the discount rate. We analyzed discount rates ranging from 0% to 5% in steps of 2.5 percentage points (**Figure S4**). We focus our discussion of the economic cost on the central scenarios in terms of discount rate (2.5%), carbon payments per hectare (Medium C Value), and DAC cost (Medium DAC Cost). In this analysis, costs are represented as net present value in the years 2075, 2100, 2200, 2300 and 2500. Higher discount rates resulted in lower net present value of carbon removal because high future costs are discounted at a higher rate.

Results

Here we focus on the (1) carbon fluxes from and to the atmosphere, (2) temperature anomalies, and (3) economic cost of the pathways. We focus our discussion on central scenarios with additional results in the Supplemental Information.

Carbon Fluxes

First, we focus on "rent only" scenarios, and the impact of maintaining contracts on the efficiency of temporary storage to contribute to CDR goals in the absence of available permanent storage. Temporary ecosystem carbon storage projects may be discontinued but replaced with a project managing a different land unit at the next timepoint. Carbon will accrue during CDR project contracts and will begin to be re-emitted to the atmosphere when the CDR project has ended and prior management is re-implemented. Although carbon is emitted to the atmosphere post-contract, the one pool soil carbon model predicts that carbon stocks will remain greater than the baseline for more than twenty years after the end of a CDR management practice (**Figure 1**). This timescale depends on the structure and parameterization of the biogeochemical model and might happen faster (or slower) in reality.

Assuming 100% renewal of cover cropping contracts, we found that enrolling the maximum land area 22.75 million hectares and renewing over the entire period sequestered a total of 136.3 Mg of carbon. At renewal rates less than 100%, the land available for new cover cropping contracts is eventually exhausted and a fraction of the land being cover cropped is allowed to revert to conventional management, and so carbon stored earlier in the simulation is released back to the atmosphere (**Figure 2A**). We calculated that maintaining enrollment of land in cover cropping longer delayed the exhaustion of available land and subsequent release of carbon back into the atmosphere beyond 2250 (**Figure 2B**). Lower renewal rates (25%) led to earlier carbon releases of 112 Mg C in 2125 out of the maximum 125 Mg C accrued, and less than 1% of accrued carbon remaining after 2175. The additional carbon stored across the patchwork was a function of the rate of carbon re-emission following management reversal.

Atmospheric carbon dynamics changed substantially when permanent carbon storage was available. We assumed that the share of released soil carbon that would be permanently removed via DACS grew as a logistic function approaching 100% in either 2050 or 2075. In all cases including permanent storage, there is net carbon removed from the atmosphere at the end of the simulation, as all carbon released after 2075 at the latest is permanently removed through DACS. However, the total amount of carbon removed depended on the maintenance of a contract (renewal rate and contract length) for temporary soil-based storage (**Figure 2, Figure S2**). We note that only for the case of low renewal rates (0%) or short contract length of 5 years (see Supplemental Information) did the released soil carbon exceed the capacity to be removed via DACS or soil carbon reenrollment early on. In these cases, larger amounts of carbon were released early in the simulation period because contract maintenance is shorter under low renewal rates with short contracts, and the initial share of released soil carbon that is compensated for by DACS under logistic growth diffusion assumptions. Carbon was re-released to the atmosphere without full replacement between 2050-2075 for the DACS 2075 logistic growth curve diffusion scenario under low renewal rates for 5-year contracts. When soil carbon contracts were maintained longer than 5 years, the delayed release of accrued carbon allowed DACS capabilities to grow and instantaneous emissions of soil carbon.

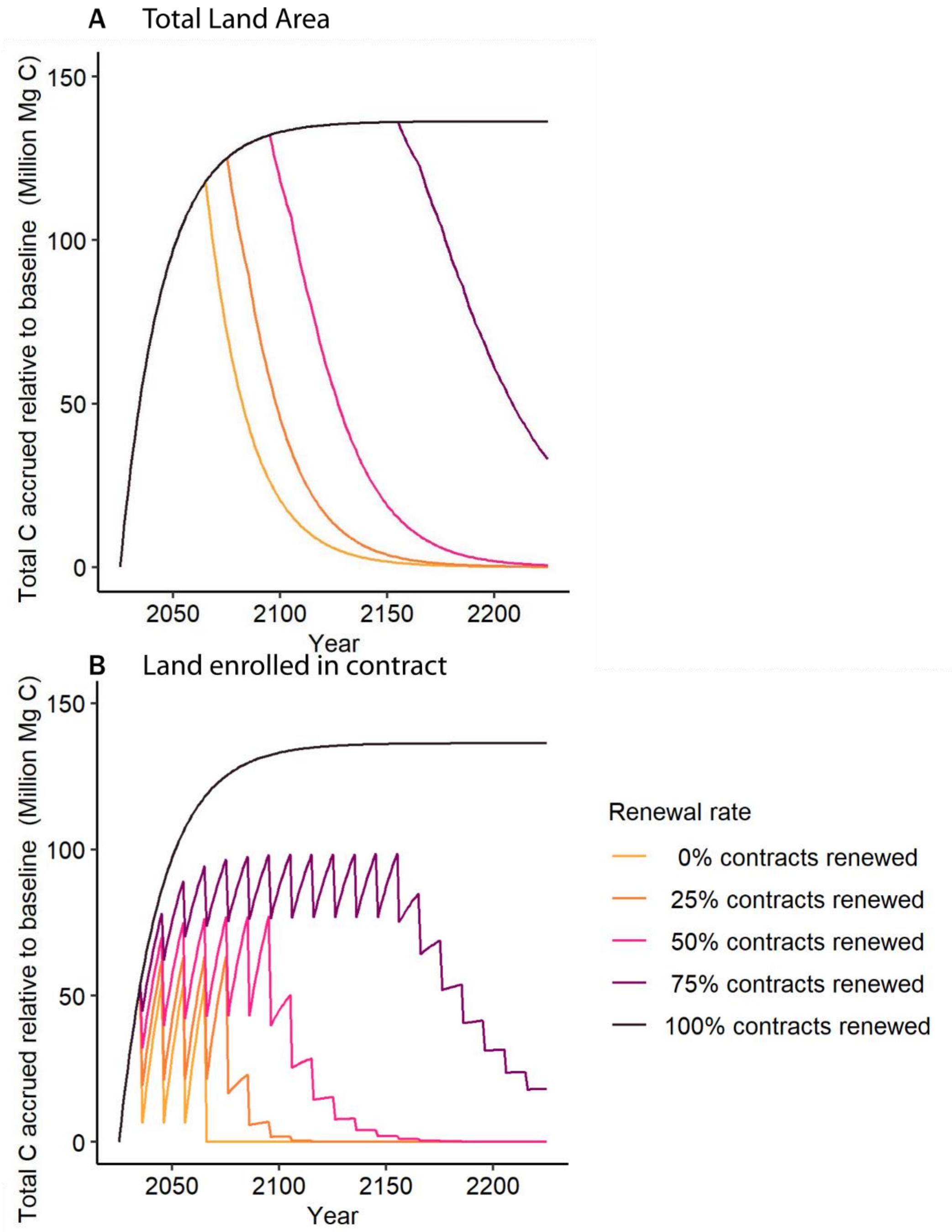

Figure 2A Soil carbon balance relative to baseline across all land uses assuming 0% contract renewal in yellow (i.e. all land under management for temporary CDR is reverted back to business as usual after one contract length), 25% (orange), 50% (pink) and 75% (maroon) contract renewal rates (i.e. 75% of land enrolled in contracts for management for temporary CDR is renewed for at least one additional contract length), and 100% (black) where the amount of land that initially went under contract is continually renewed and remains under contract throughout the entire time period. **Figure 2B** shows the total carbon balance solely in land enrolled in contracts under the same contract renewal scenarios as the top figure. Total overall C balance is highest under land with the highest renewal rates (e.g. 100%), due to maintenance of previously accrued soil C. Oscillations in C stock occur at the end of each contract period, in this case every 10 years.

Temperature Anomalies

Temperature reductions from the cases with only temporary storage and no transition to permanent storage were predictably larger and longer lasting when temporary storage contracts were maintained longer. The maximum reduction in temperature that is achieved from continuously implementing the same projects over 22.75 million ha was 227 μ°C in 2500 for SSP1-2.6 (solid line in **Figure 3**). Allocation of all resources to rapid soil carbon accrual (i.e. 0% contract renewal rates) have reduced climate mitigation impacts (>70 °μC warmer in 2075 relative to scenarios allowing contract renewal; **Table 3**), relative to scenarios which maintain storage for some period of time at lower accrual rates. Without permanent storage, all scenarios with renewal rates less than 100% resulted in only temporary warming reductions—but timing varied across scenarios. In the scenario with 10 year contracts and 75% renewal rates, temperatures are reduced below the baseline well after 2150 (**Figure 3**). However, under the lowest renewal scenarios most of the stored SOC is reemitted within 100 years and such that the cooling effect of soil carbon storage declines to zero by the end of the century.

With the introduction of permanent storage via DACS, potential temperature reductions were significantly higher than without permanent storage (**Figure 3 – solid lines**). The temperature reduction achieved was directly related to the maximum cumulative carbon stored in temporary storage prior to net carbon release. Thus, if cropland remains in the carbon-removal practice for a long time (e.g., under 75% renewal rate), more carbon accrues overtime prior to release, and this entire amount is eventually removed permanently through DACS. With permanent storage as a backstop, strategies that succeed at maintaining soil carbon storage (50-75% renewal rates) result in greater temperature reductions than strategies that do not maintain soil carbon storage, e.g. 227 μ°C (75% renewal rate) vs. 197 μ°C (0% renewal rate) in 2500 for logistic growth (2050) (**Figure 3**).

Lower renewal rates can however be compensated with longer contracts to maintain storage and achieve temperature reduction (**Figure S6**). Even with the transition to permanent storage, temperature reductions were sensitive to the successful maintenance of soil carbon storage.

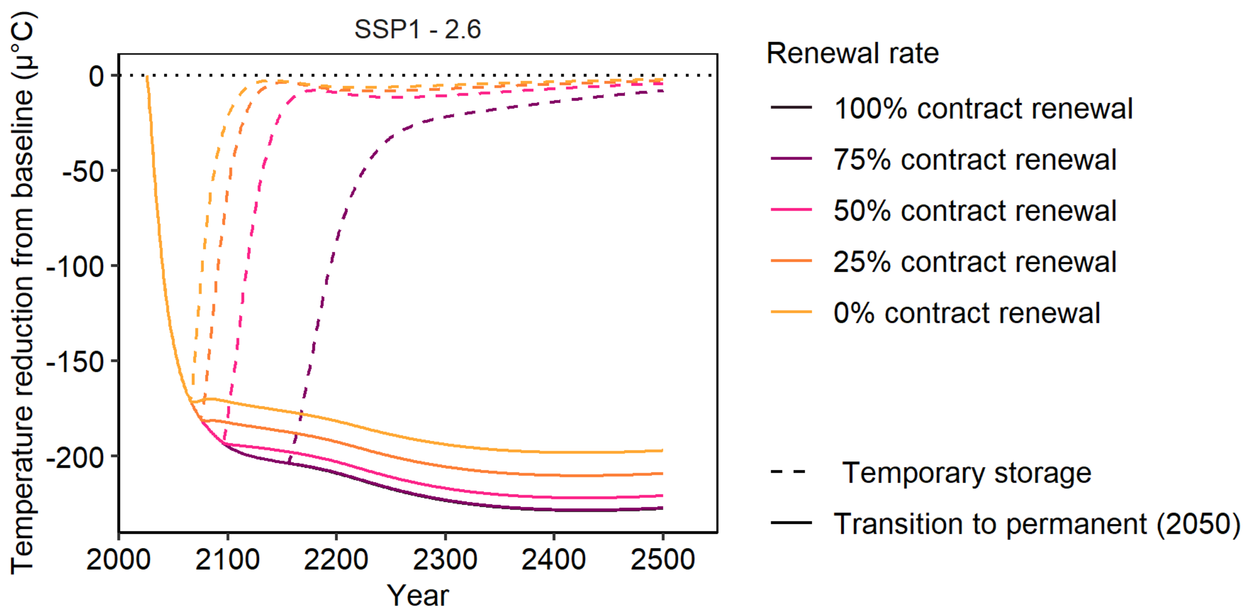

Figure 3: Warming reduction in μ°C compared to the baseline SSP1 – 2.6, for scenarios with increasing maintenance of 10 year contracts (darker color lines represent higher contract renewal rates). Dashed lines indicate temperature trajectories for temporary storage where contracts can expire. Solid lines represent temperature trajectories for continuously implemented projects (black), or for full transition of released temporary carbon storage to permanent storage (logistic growth 2050 scenario). For the case of 100% renewal rate, continuous temporary storage has the same temperature reduction trajectory as permanent storage trajectory of the same amount of carbon. Permanent storage transition scenarios store released carbon in permanent storage, with the magnitude of carbon storage depending on the maximum net carbon removed and stored in each contract renewal rate scenario.

Economic Costs

The cost of continuously "renting" temporary storage is less expensive than permanent storage via DACS, but only if the temporary carbon can be guaranteed to be maintained for centuries. To evaluate the cost of permanent storage relative to temporary storage, we compared the rent-only to the buy-only scenario, and present a range of costs across CO_2 price pathways and projected future DACS costs. In the “rent only” scenario, we implemented one carbon project on the 22.75 million ha and pay for maintenance indefinitely (100% contract renewal). In the “buy only” scenario, we replicated the carbon trajectory by purchasing permanent storage from the beginning, assuming the DAC industry can operate on that scale. One critical difference between the scenarios is that in the rent only scenario storage maintenance costs must be paid indefinitely even if the carbon accrual rate has decreased to zero. In 2050, the net present value for rent-only storage was 0.17—0.70 billion per μ°C across CO_2 price pathways compared to 1.00 – 2.60 billion USD per μ°C across DACS costs for buy-only permanent storage (**Table 1**). That difference declined by 2500 to 0.32—1.31 USD per μ°C compared to 1.37—2.19 USD per μ°C for rent-only and buy-only respectively, because payments for DACS are (conceptually) zero after the soil approaches the new long-run equilibrium.

For temporary storage without a bridge to permanent storage, the economic cost of changing temperature varied substantially over the time considered (**Figure 4**). Due to the linearity of the soil carbon model, the cost and temperature anomaly through 2050 were identical independent of the contract length and renewal rate chosen. Divergences between scenarios began in 2075 and beyond. In our forecasts of 2100 and beyond, the cost per μ°C of temperature reduction of low renewal rates (i.e., 0% - 50% renewal) was relatively high because the cooling effect of temporary carbon storage approaches zero. Low renewal rates cost 0.30–6.96 billion USD per μ°C reduction across CO_2 price pathways in 2100 compared to cheaper costs of 0.23—1.07 billion USD per μ°C for high renewal rates of 75-100%. This pattern was accentuated when we considered longer time frames, with increasing cost for shorter contracts and lower renewal rates due to both cost of maintenance and diminishing temperature reductions as carbon is released.

Transitioning fully from temporary storage to permanent storage within the century were the most cost-effective storage pathways that included permanent storage. With transition to permanent storage via DACS, the short-run outcomes by 2050 had the same temperature reduction of 141.4 μ°C, and ranged in cost from 0.21–0.92 billion USD per μ°C across DACS costs, with identical carbon removal and costs across renewal rate cases. With permanent storage backstops in 2050 or 2075, the cost per μ°C increased through 2100-2200. In the very long run, i.e., 2500, the cost per μ°C decreased with increasing warming reductions. As in the previous case with temporary storage only, cases with longer enrollment periods (i.e. higher renewal rates) were cheaper per μ°C and achieve a larger cooling effect, as temporary storage had to be replaced with permanent storage earlier at a higher cost. For the example of the logistic growth of DACS (2050), a contract length of 10 years with a 75% renewal rate led to a 2100 warming reduction of 227.5 μ°C at a cost of 0.49 billion USD per μ°C whereas a 0% renewal rate led to a lower warming reduction of 197.1 μ°C and cost 0.53 billion USD per μ°C for the moderate DACS cost trajectory. Both rent-then-buy transition pathway with logistic growth of DACS achieved the same temperature reductions as the buy-only permanent storage pathway (227.2 μ°C for 75% renewal rate), but for lower costs of 0.18-0.76 USD per μ°C compared to 0.56—1.37 USD per μ°C for permanent storage only.

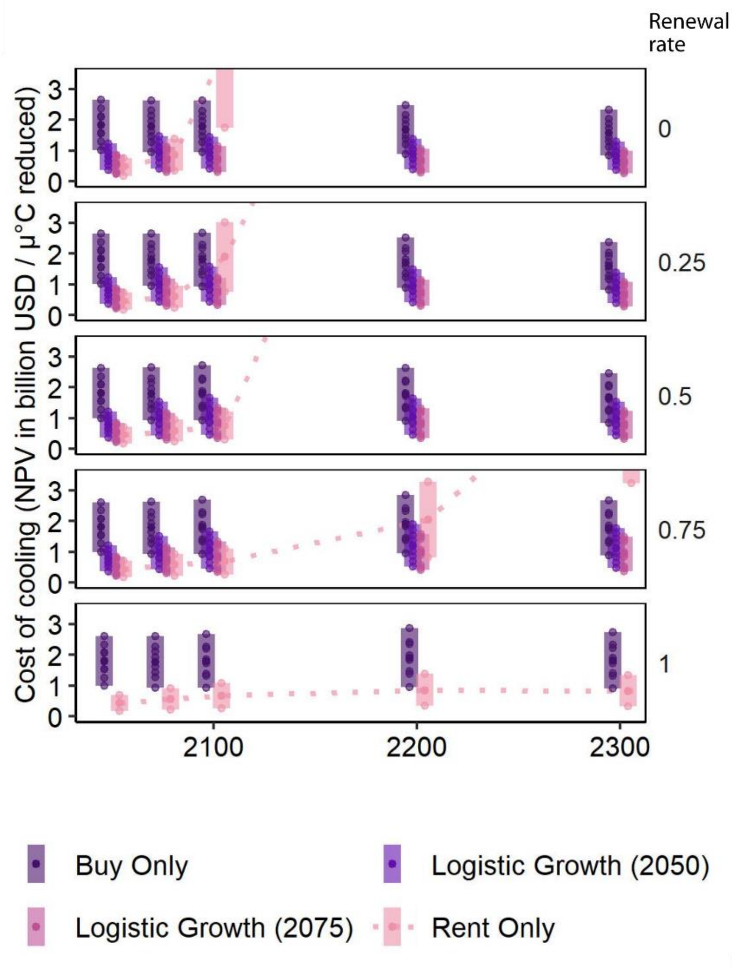

Figure 4: The cumulative cost of cooling is given as net present value per degree of warming

reduced from an SSP1 – 2.6 baseline for each CDR scenario. Points are presented for each year on the x-axis, note that net present value is calculated on a cumulative basis and thus is not an annual cost rate. Each panel represents a different contract renewal rate (as fractions) for temporary storage, increasing from top (0% renewal) to bottom (100% renewal). Temporary storage (“rent only”) without permanent storage is represented as pink rectangles, which vary by projected future values of CO_2 (low, medium, and high) and are independent of DACS cost uncertainty. The dashed pink line illustrates the trend over time of the cost of renting temporary storage, which increases as carbon is released and the temperature effect approaches zero and far exceeds the y-axis. Ranges for the permanent storage scenarios including the transition scenarios from temporary to permanent storage by 2050 (purple) and 2075 (maroon) and for the “buy only” permanent storage scenario are given as vertical rectangles, which represent the maximum and minimum calculated net present value given three trajectories for future CO_2 prices and for future DACS costs (low, moderate, and high).

Year	Buy only		Rent only		Rent-then-buy	
	Warming reduced (µ°C)	**Cost (Billion USD per µ°C)**	**Warming reduced (µ°C)**	**Cost (Billion USD per µ°C)**	**Warming reduced (µ°C)**	**Cost (Billion USD per µ°C)**
	0% Renewal					
2050	141	1.84—1.01	141	0.19—0.75	141	0.21—0.93
2075	171	1.79—0.95	109	0.35—1.38	164—171	0.23—0.94
2100	171	1.79—0.95	22	1.74—6.96	163—171	0.23—0.94
2500	197	1.55—0.83	2	16.36—65.44	188—197	0.20—0.81
	50% Renewal					
2050	141	1.01—2.63	141	0.18—0.73	141	0.21—0.93
2075	180	0.94—2.65	180	0.24—0.95	180	0.22—0.93
2100	194	0.9—2.71	178	0.30—1.20	194	0.21—0.89
2500	221	0.83—2.42	5	12.33—49.35	221	0.19—0.78
	100% Renewal					
2050	141	1.00—2.60	141	0.17—0.70	—	—
2075	181	0.93—2.61	181	0.23—0.91	—	—
2100	195	0.92—2.67	195	0.27—1.07	—	—
2500	228	1.37—2.19	228	0.32—1.31	—	—

Table 1: Global temperature reduction relative to a baseline SSP1 - 2.6 temperature trajectory

given a permanent storage (Buy Only) and 10 y temporary storage contracts (Rent Only) from no contract renewals (0%) to continuous renewal rates (100%). The range of net present value for each year were divided by warming reduction in that year to give the cost of cooling in billion USD per μ°C. The range of net present value for buy-only is based on the minimum and maximum values depending on three future DACS cost trajectories, and the rent-then-buy ranges span the same DACS cost trajectory ranges, three future CO_2 price trajectories, as well as both the logistic growth (2050) and logistic growth (2075). Rent-then-buy outcomes are given for 0% and 50% temporary contract renewal rates. Rent-then-buy outcomes are equivalent to rent-only outcomes for 100% renewal, as all carbon stays in temporary storage without any replacement of contracts for the 100% renewal rate.

Discussion

Our results illustrate how a patchwork of temporary CDR projects can potentially yield warming reductions over multi-decadal timescales—but only if the patchwork is well maintained. Consistent with earlier analyses (Wise *et al* 2019), we found that even though carbon stored in ecosystems is vulnerable to re-emission, lost carbon can be replaced by expansion of CDR to different land. This extends the cooling effect of ecosystem CDR beyond the timescale at which C from an individual lapsed project is re-emitted. The durability of ecosystem CDR is thus not only a function of biophysical factors but also depends on the rate at which CDR projects are replaced. Determining the value of ecosystem CDR in a net-zero world consequently requires accurate forecasts of how successfully ecosystem C storage will be maintained.

Our analysis also shows that maintaining ecosystem C stocks even after C accrual has slowed is necessary to achieve an appreciable short-term cooling effect. Specifically, our findings in the absence of permanent storage suggest that longer ecosystem CDR enrollment and higher renewal rates lead to higher temperature reduction compared to the baseline. Releasing temporarily-stored carbon prior to a climate tipping point can exacerbate climate forcing, whereas releasing it after can mitigate climate change (Jorgensen *et al* 2015), albeit not at the same timescale as permanent storage. Therefore, contrary to crediting practices that pay temporary projects per ton of CO_2 stored, maximizing short bursts of high soil-based CDR accrual rates is not necessarily the most efficient way to achieve climate change mitigation. Incentivizing practices that maintain ecosystem C storage even when C accrual has ceased may be more efficient over the long run.

Our forecasts of ecosystem CDR potential over time depend heavily on our assumptions regarding land manager behavior. For instance, we conservatively assumed that managers will only adopt a CDR practice if they have a contract, and that they immediately end the practice after the contract ends. The first assumption is supported by studies showing that farmers are most likely to adopt a new practice when they will receive short-term economic benefits (Piñeiro *et al* 2020, Kuehne *et al* 2017). The second assumption may be overly conservative: for instance, federal programs in the United States such as the Conservation Reserve Program have reported 20–60 % of farmers maintaining practices after paid contracts expire (Sullins *et al* 2021, Bigelow *et al* 2020). On the other hand, voluntary conservation practices are much more sensitive to reversal during years with productive weather conditions and profitable crop prices (Sullins *et al* 2021). This suggests that contracts offer some protection against short term management reversals, and that it would be risky to assume the continuation of C-storing practices after payments have ceased.

We avoided making specific assumptions regarding the duration of ecosystem CDR contracts or the rate at which contracts are renewed, instead exploring a range of contract lengths and renewal rates. While we explored contract lengths up to 20 years (Supplemental Information), shorter contracts are economically preferred for land managers under results-based payment frameworks due to declining soil carbon accrual rates and rising marginal costs (Gulati and Vercammen 2005). This is consistent with the observation that shorter contracts are typical of the voluntary carbon market (Zelikova *et al* 2021). Even under payment-for-practice framework, long contracts that ensure maintenance of carbon storage are not commonly tenable in private agricultural settings. Shorter contracts (5-10 years) may thus be more representative of reality. On the other hand, intermediate to high renewal rates (50-75%) may not be unrealistic given that a majority of landowners prefer to re-enroll in practice-based conservation programs over time (Sullins *et al* 2021, Barnes *et al* 2020). Nonetheless, relying on the same patch of agricultural land to be continuously managed for soil-based CDR indefinitely is unrealistic due to landowner preferences for short contracts (Wise *et al* 2019) and the challenge of predicting future landowner behavior. Shifting patchworks of management, corresponding to renewal rates less than 100% in our analysis, are more realistic.

Critically, we assumed that soil-based CDR projects that lapse will be replaced with new projects until all available land is exhausted, after which CDR halts. This assumption has a major impact on our analysis because the exhaustion of available land ultimately forces re-emission of stored carbon. If land that had previously been enrolled in carbon storage were allowed to re-enroll, CDR patchworks with lower contract renewal rates would behave more like the maximally optimistic 100% renewal case. We nonetheless imposed a limit on land availability to illustrate the effect of correlated risk across the CDR patchwork, whereby maintenance of the entire patchwork could fail at some point in time. Exhaustion of available land thus serves as a stand-in for any number of systemic risks: a widespread drop in landowner participation due to economic or environmental factors or disruptions to institutional climate-mitigation commitments. The time that elapses before this limit is reached is determined by contract lengths and renewal rates, meaning that each scenario reflects a general assumption that high-turnover CDR patchworks are likely to fail sooner than more stable patchworks.

While maintaining temporary storage for a long period of time appears to be a high value option, the reemission risk is much higher than any scenario for which permanent storage is phased in at some point. Our results show that transitioning from the beneficial low initial costs of temporary CDR storage in the near-term to the climate-security of permanent CDR storage before the end of the century partly limits the risks associated with relying on temporary CDR and achieves a lower cost than the extreme "rent only" and "buy only" strategies. The scenarios with a backstop for permanent storage vias DACS are like those proposed by Herzog et al (2003), and illustrate the idea that temporary storage can act as a bridge to permanent storage in the long term (Sedjo and Marland 2003). Our results support the concept that the value of any temporary storage decreases the further climate change progresses and the warmer mean global surface temperatures become (Herzog *et al* 2003).

Relying on temporary storage as a bridge to permanent storage appears to be cost effective in our analysis, but this result only emerges under the assumption that both commitments to maintenance of temporary storage and transition to permanent storage are honored. One strategy to manage the risks associated with of phased commitments which include an initial period of ecosystem carbon rental would be to apply the principle of "like-for-like" carbon accounting schemes, which balance ecosystem CDR against reversible emissions from land use (Schenuit *et al*

2023, Moura Costa and Wilson 2000, Fearnside *et al* 2000). In this case the total amount of rented carbon storage would be limited to neutralizing land use emissions at a jurisdictional level, and a lapsed commitment would not be responsible for unmitigated fossil fuel emissions. Another approach to minimizing risk would be to limit the duration of temporary storage by replacing ecosystem C with geological storage faster—but this option would come at a higher cost (**Figure 4**). Combining near term ecosystem storage with a permanent storage backstop thus represents a spectrum of strategies, with a tradeoff between high-cost, low-risk early adoption of geologic storage and lower-cost, higher-risk delayed adoption.

It is important to recognize that the cost declines assumed for permanent storage via DACS technologies rely in part on the scaling up of deployment of permanent storage, despite these costs being treated as exogenous for the purposes of this analysis. There is some risk that delaying the adoption of permanent storage using temporary removals in turn delays the deployment of and the associated cost reductions in permanent storage. To avoid this, there is a role for institutions to invest some resources in developing permanent storage technologies today, even if these may not represent the most cost-optimal near-term mitigation approach compared to temporary removals.

Finally, the value of any form of storage—whether temporary or permanent—is strongly dependent on the underlying mitigation pathway (Mayer *et al* 2018). Removals are less effective in reducing global temperatures under high emissions pathways, and both horizontal stacking of temporary removals and permanent removals are more expensive than many other forms of mitigation in the near-term. Policymakers need to balance both responsibility and cost when determining the optimal levels of CDR deployment, and the value of CDR will tend to increase as the world gets closer to net zero (Rogelj *et al* 2018b, 2018a) and other lower-cost mitigation options are exhausted both at sector and economy-wide levels.

Conclusions

Stacking reversible soil CO_2 removal and storage over time can contribute to reducing peak temperatures, and maintaining carbon storage in ecosystems for longer leads to larger and more sustained temperature reductions. Renting temporary ecological CO_2 removal and storage century can be a bridge to buying permanent CO_2 storage in the long-term. Transitioning from renting to buying CO_2 removal and storage within this century may yield temperature reductions at a lower cost than alternative storage pathways. However, this result requires that the commitment to transition from ecosystem storage to permanent storage is upheld. Consequently, this strategy is riskier than immediate deployment of permanent storage because maintenance of temporary storage and commitments to permanent storage might lapse. This risk would likely shorten the optimal deployment timelines of temporary storage. Quantifying this risk accurately is likely essential for using ecosystem CDR as an effective bridge to permanent carbon storage.

Acknowledgements

Portions of this work were performed at Lawrence Livermore National Laboratory under the auspices of U.S. Department of Energy contract DE-AC52-07NA27344 and was supported by Laboratory Directed Research and Development funding under project number 24-SI-002 (LLNL-JRNL-2002437). This work was also funded through the Roads to Removal Project. Thank you to C. Kelly and K. Georgiou for initial feedback on methods.

References

Agbo P, An K, Baker S E, Cross J, Kreibe L, Li W, Myers C, Pang S H, Schaef H T, Schaidle J A, Scown C D, Sherwin E D, Subban C, Villante M and Yadav G 2024 *Technological Innovation Opportunitites for CO2 Removal* (Department of Energy)

Allen M R, Friedlingstein P, Girardin C A J, Jenkins S, Malhi Y, Mitchell-Larson E, Peters G P and Rajamani L 2022 Net Zero: Science, Origins, and Implications *Annual Review of Environment and Resources* **47** 849–87

Barnes J C, Sketch M, Gramza A R, Sorice M G, Iovanna R and Dayer A A 2020 Land use decisions after the Conservation Reserve Program: Re-enrollment, reversion, and persistence in the southern Great Plains *Conservat Sci and Prac* **2** e254

Bigelow D, Claassen R, Hellerstein D, Breneman V, Williams R and You C 2020 *The Fate of Land in Expiring Conservation Reserve Program Contracts, 2013-16* (U.S. Department of Agriculture, Economic Research Service) Online: https://www.ers.usda.gov/webdocs/publications/95642/eib-215.pdf?v=5740.2

Blanco-Canqui H 2022 Cover crops and carbon sequestration: Lessons from U.S. studies *Soil Science Society of America Journal* **86** 501–19

Blanco-Canqui H, Ruis S J, Proctor C A, Creech C F, Drewnoski M E and Redfearn D D 2020 Harvesting cover crops for biofuel and livestock production: Another ecosystem service? *Agronomy Journal* **112** 2373–400

Brunner C, Hausfather Z and Knutti R 2024 Durability of carbon dioxide removal is critical for Paris climate goals *Commun Earth Environ* **5** 645

Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne P W, Trisos C, Romero J, Aldunce P, Barrett K, Blanco G, Cheung W W L, Connors S, Denton F, Diongue-Niang A, Dodman D, Garschagen M, Geden O, Hayward B, Jones C, Jotzo F, Krug T, Lasco R, Lee Y-Y, Masson-Delmotte V, Meinshausen M, Mintenbeck K, Mokssit A, Otto F E L, Pathak M, Pirani A, Poloczanska E, Pörtner H-O, Revi A, Roberts D C, Roy J, Ruane A C, Skea J, Shukla P R, Slade R, Slangen A, Sokona Y, Sörensson A A, Tignor M, Van Vuuren D, Wei Y-M, Winkler H, Zhai P, Zommers Z, Hourcade J-C, Johnson F X, Pachauri S, Simpson N P, Singh C, Thomas A, Totin E, Arias P, Bustamante M, Elgizouli I, Flato G, Howden M, Méndez-Vallejo C, Pereira J J, Pichs-Madruga R, Rose S K, Saheb Y, Sánchez Rodríguez R, Ürge-Vorsatz D, Xiao C, Yassaa N, Alegría A, Armour K, Bednar-Friedl B, Blok K, Cissé G, Dentener F, Eriksen S, Fischer E, Garner G, Guivarch C, Haasnoot M, Hansen G, Hauser M, Hawkins E, Hermans T, Kopp R, Leprince-Ringuet N, Lewis J, Ley D, Ludden C, Niamir L, Nicholls Z, Some S, Szopa S, Trewin B, Van Der Wijst K-I, Winter G, Witting M, Birt A, et al 2023 *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* (Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC)) Online: https://www.ipcc.ch/report/ar6/syr/

Caruso T, Vries F T D, Bardgett R D and Lehmann J 2018 Soil organic carbon dynamics matching ecological equilibrium theory *Ecology and Evolution* **8** 11169–78

Chaplot V and Smith P 2023 Cover crops do not increase soil organic carbon stocks as much as has been claimed: What is the way forward? *Global Change Biology* **29** 6163–9

Fajardy M, Patrizio P, Daggash H A and Mac Dowell N 2019 Negative Emissions: Priorities for Research and Policy Design *Front. Clim.* **1** 6

Fearnside P M, Lashof D A and Moura-Costa P 2000 Accounting for time in Mitigating Global Warming through land-use change and forestry *Mitigation and Adaptation Strategies for Global Change* **5** 239–70

Fuhrman J, Bergero C, Weber M, Monteith S, Wang F M, Clarens A F, Doney S C, Shobe W and McJeon H 2023 Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system *Nat. Clim. Chang.* **13** 341–50

Gulati S and Vercammen J 2005 The Optimal Length of an Agricultural Carbon Contract *Canadian Journal of Agricultural Economics/Revue canadienne d’agroeconomie* **53** 359–73

Guzzardi M, Chen T, Servais-Laval Q, Niparko K, Höglund R and Rink A 2024 2024+Market Outlook Summary Report *CDR.fyi* Online: https://www.cdr.fyi/blog/2024-market-outlook-summary-report

Herzog H, Caldeira K and Reilly J 2003 An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage *Climatic Change* **59** 293–310

Jian J, Du X, Reiter M S and Stewart R D 2020 A meta-analysis of global cropland soil carbon changes due to cover cropping *Soil Biology and Biochemistry* **143** 107735

Johnston A E, Poulton P R and Coleman K 2009 Chapter 1 Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes vol 101, ed D L B T-A in A Sparks (Academic Press) pp 1–57 Online: http://www.sciencedirect.com/science/article/pii/S0065211308008018

Jorgensen S, Hauschild M and Nielsen P 2015 The potential contribution to climate change mitigation from temporary carbon storage in biomaterials *INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT* **20** 451–62

Kuehne G, Llewellyn R, Pannell D J, Wilkinson R, Dolling P, Ouzman J and Ewing M 2017 Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy *Agricultural Systems* **156** 115–25

Leifeld J and Keel S G 2022 Quantifying negative radiative forcing of non-permanent and permanent soil carbon sinks *Geoderma* **423** 115971

LLNL 2023 *Roads to removal: Options for carbon dioxide removal in the United States* (Lawrence Livermore National Laboratory)

Marland G, Fruit K and Sedjo R 2001 Accounting for sequestered carbon: the question of permanence *Environmental Science & Policy* **4** 259–68

Matthews H D, Zickfeld K, Dickau M, MacIsaac A J, Mathesius S, Nzotungicimpaye C-M and Luers A 2022 Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario *Commun Earth Environ* **3** 65

Mayer A, Hausfather Z, Jones A D and Silver W L 2018 The potential of agricultural land management to contribute to lower global surface temperatures *Science Advances* **4** eaaq0932–eaaq0932

McClelland S C, Paustian K and Schipanski M E 2021 Management of cover crops in temperate climates influences soil organic carbon stocks: a meta-analysis *Ecological Applications* **31** e02278

Millar R J, Nicholls Z R, Friedlingstein P and Allen M R 2017 A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions *Atmospheric Chemistry and Physics* **17** 7213–28

Minx J C, Lamb W F, Callaghan M W, Fuss S, Hilaire J, Creutzig F, Amann T, Beringer T, De Oliveira Garcia W, Hartmann J, Khanna T, Lenzi D, Luderer G, Nemet G F, Rogelj J, Smith P, Vicente Vicente J L, Wilcox J and Del Mar Zamora Dominguez M 2018 Negative emissions—Part 1: Research landscape and synthesis *Environ. Res. Lett.* **13** 063001

Moura Costa P and Wilson C 2000 An equivalence factor between CO2 avoidedemissions and sequestration – description andapplications in forestry *Mitigation and Adaptation Strategies for Global Change* **5** 51–60

Newton J 2019 More than 140 million acres in federal farm conservation programs *Market Intel : American Farm Bureau Federation* Online: https://www.fb.org/market-intel/more-than-140-million-acres-in-federal-farm-conservation-programs

Nicholls Z R J, Meinshausen M, Lewis J, Gieseke R, Dommenget D, Dorheim K, Fan C-S, Fuglestvedt J S, Gasser T, Golüke U, Goodwin P, Hartin C, Hope A P, Kriegler E, Leach N J, Marchegiani D, McBride L A, Quilcaille Y, Rogelj J, Salawitch R J, Samset B H, Sandstad M, Shiklomanov A N, Skeie R B, Smith C J, Smith S, Tanaka K, Tsutsui J and Xie Z 2020 Reduced Complexity Model Intercomparison Project Phase 1: introduction and evaluation of global-mean temperature response *Geoscientific Model Development* **13** 5175–90

Nseir A and Honig L 2022 US farmers expect to plant more soybeans and less corn acreage *United States Department of Agricultural National Agricultural Statistics Service News Releases* Online: https://www.nass.usda.gov/Newsroom/archive/2022/03-31-2022.php

Pett-Ridge J, Kuebbing S, Mayer A C, Hovorka S, Pilorgé H, Baker S E, Pang S H, Scown C D, Mayfield K K, Wong A A, Aines R D, Ammar H Z, Aui A, Ashton M, Basso B, Bradford M, Bump A P, Busch I, Calzado E R, Chirigotis J W, Clauser N, Crotty S, Dahl N, Dai T, Ducey M, Dumortier J, Ellebracht N C, Egui R G, Fowler A, Georgiou K, Giannopoulos D, Goldstein H M, Harris T, Hayes D, Hellwinckel C, Ho A, Hong M, Hunter-Sellars E, Kirkendall W, Langholtz M, Layer M, Lee I, Lewis R, Li W, Liu W, Lozano J T, Lunstrum A, McNeil W, Nico P, O'Rourke A, Paustian K, Peridas G, Pisciotta M, Price L, Psarras P, Robertson G P, Sagues W J, Sanchez D L, Schmidt B M, Slessarev E W, Sokol N, Stanley A J, Swan A, Toureene C, Wright M M, Yao Y, Zhang B and Zhang Y 2023 *Roads to Removal: Options for Carbon Dioxide Removal in the United States* (United States) Online: https://www.osti.gov/biblio/2301853

Piñeiro V, Arias J, Dürr J, Elverdin P, Ibáñez A M, Kinengyere A, Opazo C M, Owoo N, Page J R, Prager S D and Torero M 2020 A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes *Nat Sustain* **3** 809–20

Poffenbarger H J, Barker D W, Helmers M J, Miguez F E, Olk D C, Sawyer J E, Six J and Castellano M J 2017 Maximum soil organic carbon storage in Midwest U.S. cropping systems when crops are optimally nitrogen-fertilized ed X Wang *PLoS ONE* **12** e0172293

Riahi K, van Vuuren D P, Kriegler E, Edmonds J, O'Neill B C, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Cuaresma J C, KC S, Leimbach M, Jiang L, Kram T, Rao S, Emmerling J, Ebi K, Hasegawa T, Havlik P, Humpenöder F, Da Silva L A, Smith S, Stehfest E, Bosetti V, Eom J, Gernaat D, Masui T, Rogelj J, Strefler J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Baumstark L, Doelman J C, Kainuma M, Klimont Z, Marangoni G, Lotze-Campen H, Obersteiner M, Tabeau A and Tavoni M 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview *Global Environmental Change* **42** 153–68

Rogelj J, Popp A, Calvin K V, Luderer G, Emmerling J, Gernaat D, Fujimori S, Strefler J, Hasegawa T, Marangoni G, Krey V, Kriegler E, Riahi K, van Vuuren D P, Doelman J, Drouet L, Edmonds J, Fricko O, Harmsen M, Havlík P, Humpenöder F, Stehfest E and Tavoni M 2018a Scenarios towards limiting global mean temperature increase below 1.5 °C *Nature Climate Change* **8** 325–32

Rogelj J, Shindell D, Jiang K, Fifita S, Ginzburg V, Handa C, Kheshgi H, Kobayashi S, Kriegler E, Mundaca L, Séférian R and Vilariño M V 2018b 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* ed V Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, and J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press) pp 93–174 Online: https://doi.org/10.1017/9781009157940.004

Ruis S J, Blanco-Canqui H, Creech C F, Koehler-Cole K, Elmore R W and Francis C A 2019 Cover Crop Biomass Production in Temperate Agroecozones *Agronomy Journal* **111** 1535–51

Schenuit F, Gidden M J, Boettcher M, Brutschin E, Fyson C, Gasser T, Geden O, Lamb W F, Mace M J, Minx J and Riahi K 2023 Secure robust carbon dioxide removal policy through credible certification *Commun Earth Environ* **4** 349

Sedjo R A and Marland G 2003 Inter-trading permanent emissions credits and rented temporary carbon emissions offsets: some issues and alternatives *Climate Policy* **3** 435–44

Smith C J, Forster P M, Allen M, Leach N, Millar R J, Passerello G A and Regayre L A 2018 FAIR v1.3: a simple emissions-based impulse response and carbon cycle model *Geosci. Model Dev.* **11** 2273–97

Smith S, Geden O, Gidden M, Lamb W F, Nemet G F, Minx J, Buck H, Burke J, Cox E, Edwards M, Fuss S, Johnstone I, Müller-Hansen F, Pongratz J, Probst B, Roe S, Schenuit F, Schulte I and Vaughan N 2024 The State of Carbon Dioxide Removal - 2nd Edition Online: https://osf.io/f85qj/

Strefler J, Kriegler E, Bauer N, Luderer G, Pietzcker R C, Giannousakis A and Edenhofer O 2021 Alternative carbon price trajectories can avoid excessive carbon removal *Nat Commun* **12** 2264

Sullins D S, Bogaerts M, Verheijen B H F, Naugle D E, Griffiths T and Hagen C A 2021 Increasing durability of voluntary conservation through strategic implementation of the Conservation Reserve Program *Biological Conservation* **259** 109177

Tautges N E, Chiartas J L, Gaudin A C M, O'Geen A T, Herrera I and Scow K M 2019 Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils *Global Change Biology* **25** 3753–66

Wise L, Marland E, Marland G, Hoyle J, Kowalczyk T, Ruseva T, Colby J and Kinlaw T 2019 Optimizing sequestered carbon in forest offset programs: balancing accounting stringency and participation *Carbon Balance and Management* **14** 16

Zelikova J, Chay F, Freeman J and Cullenward D 2021 A buyer's guide to soil carbon offsets *CarbonPlan* Online: https://carbonplan.org/research/soil-protocols-explainer

Zhang Y, Marx E, Williams S, Gurung R, Ogle S, Horton R, Bader D and Paustian K 2020 Adaptation in U.S. Corn Belt increases resistance to soil carbon loss with climate change *Sci Rep* **10** 13799

Supplemental Information for *Cost of cooling: The value of reversible carbon storage in a zero-emissions world*

2025

Authors: Allegra Mayer[1], Jerome Dumortier[2], Zeke Hausfather[3], Jennifer Pett-Ridge[1,4,5], Eric Slessarev[6,7]

Affiliations:

[1] Lawrence Livermore National Laboratory, Physical Life Sciences Division, Livermore, CA, USA

[2] Indiana University Indianapolis, O'Neill School of Public and Environmental Affairs, Indianapolis, IN, USA

[3] Stripe Inc., South San Francisco, CA USA

[4] Life and Environmental Sciences Department, University of California, Merced, CA, USA

[5] Innovative Genomics Institute, University of California, Berkeley, CA USA

[6] Yale University, Department of Ecology and Evolutionary Biology, New Haven, CT, USA

[7] Yale University, Yale Center for Natural Carbon Capture, New Haven, CT, USA

1 Transition from Temporary to Permanent CDR

There is a significant uncertainty about the diffusion path of DACS over time. To cover a range of possibilities and also the two extreme cases of 100% diffusion in 2025 and no diffusion at all over
the time period until 2500, we assumed various diffusion pathways. In the *Rent Only* scenario, we assumed that carbon is sequestered in soils until 2500 with no DACS available. The scenario *Buy Only* represents the opposite case where all carbon removed from the atmosphere is permanently placed in geologic storage. The logistic growth scenarios assume a S-shaped growth until 2050 or 2075 in the percentage of carbon that is removed through DACS (**Figure S1a**). Those growth functions are consistent with technology diffusion curves (Rogers, 1962). The logistic growth curves are written as follows:

$$s_t = \left[1 + \left(\frac{1 - s_0}{s_0}\right) e^{-rt}\right]^{-1}$$

with r being calibrated such that $s_0 = 0.01$ and $s_t = 0.95$ in 2050 or 2075.

The results of the various DACS diffusion pathways depended on both the backstop for permanent geologic storage (2025, 2050, or 2075), and the renewal rate for temporary carbon storage, as this determined the timing of carbon released from temporary storage and replaced with permanent storage (**Figure S2**).

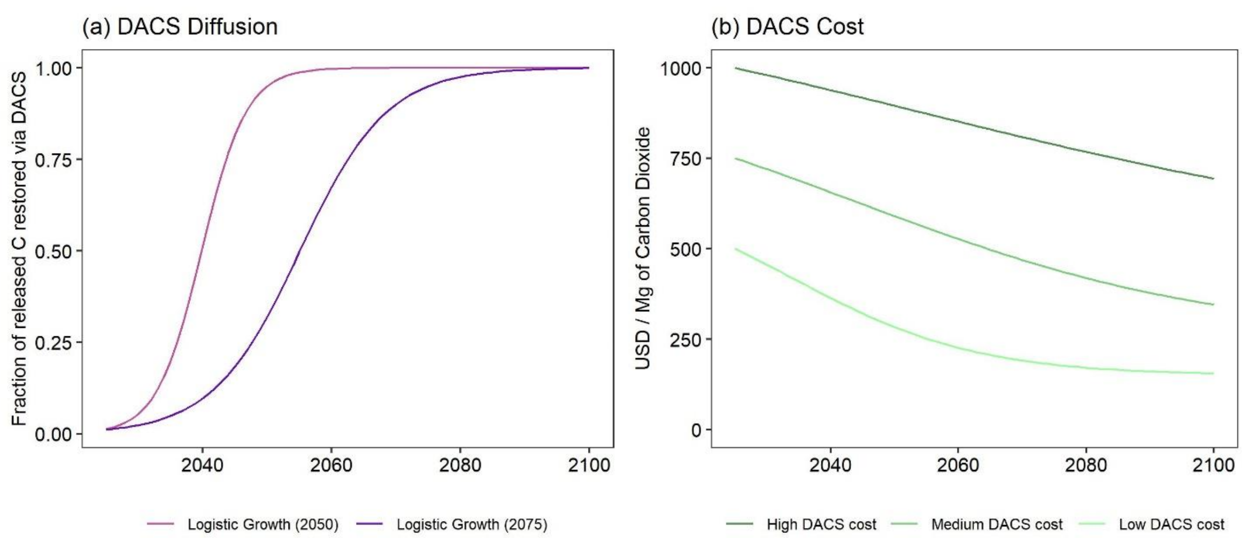

Figure S1. DACS diffusion trajectories representing the use of permanent carbon removal as opposed to temporary removal. The logistic growth curves are based on Equation 3. Except for the rent only scenario, 100% DAC use is assumed past 2100.

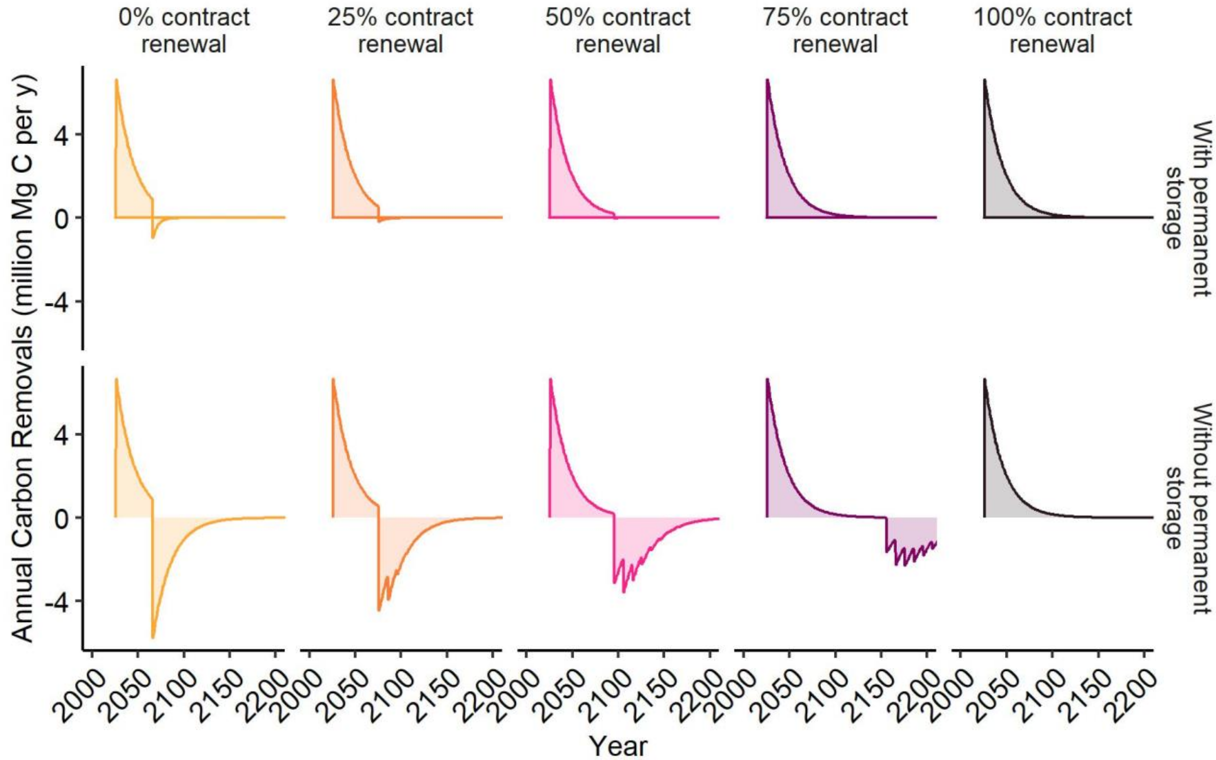

Figure S2: The rate of annual atmospheric carbon removal is shown here for contract cases (0% - 100% renewal rates from left to right) for each scenario of growth of permanent storage via DACS. In the bottom panels, lines show the "rent only" cases of temporary carbon removals without permanent storage, leading to remission (negative carbon removals) in the second half of the century, except in the 100% renewal case. In the top panels, the solid lines represent "buy only" where all carbon that would have been removed temporarily in soils is instead removed via DACS from the beginning, and "rent-then-buy" bridge scenario where released temporary carbon is replaced with permanent storage by 2050 or 2075.

2 Direct Air Capture Cost Trajectories

The technology considered for permanent CO_2 removal from the atmosphere is Direct Air Capture with subsequent geological storage (DACS). There is significant uncertainty regarding the level, timing, and path of achieving long-run cost. Current cost estimates are in the \$600–\$1000 range per metric ton (Mg) of CO_2-e removed (McQueen et al., 2021).[1] The cost range in the long-run varies widely from below \$60 by 2040 to \$280 by 2050 per Mg of CO_2-e (LLNL, 2023; Sutherland, 2016). We generate three potential cost paths with starting values for the low, medium, and high DACS cost curves of \$500, \$750, and \$1,000 per Mg^{-1} CO_2-e, respectively. The long-run prices are \$150, \$250, \$500 per Mg^{-1} CO_2-e in the long run (Figure **S1b**).

[1]See also Unlocking the potential of direct air capture: Is scaling up through carbon markets possible? published by the International Energy Agency on 11 May 2023.

3 Carbon Price Path and Payment Policy

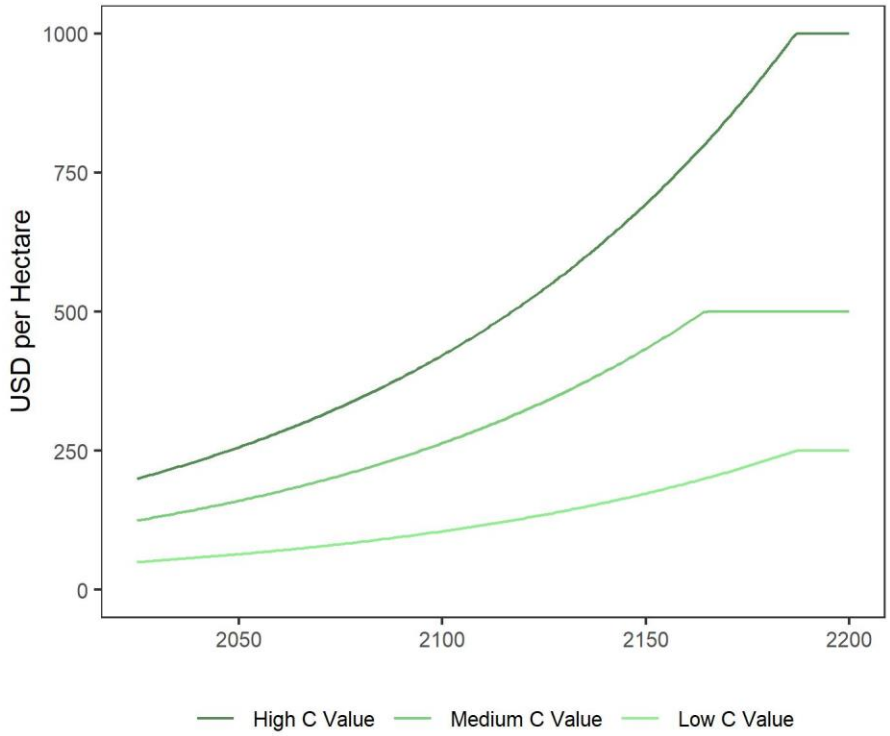

Figure S3. Future trajectories for the value of implementing a practice to remove and store CO_2 in a hectare of land depending on the future value of CO_2 (carbon price paths), given in $ per hectare.

We considered three carbon value paths, labelled *Low CO_2 Value*, *Medium CO_2 Value*, and *High CO_2 Value*. The carbon price is in USD per Mg of CO_2-equivalent (CO_2-e). The growth rate for each path is set to 2% and the starting values are $50, $125, and $200 for low, medium, and high price paths, respectively. For the three price paths, we assume that the maximum CO_2 value is $250, $500, and $1000 for the low, medium, and high CO_2 value respectively. As with other components of our analysis, there is substantial uncertainty regarding the payment to farmers for temporary carbon removal and storage. Note that unlike in Herzog et al. (2003), there is the possibility that the carbon price grows at a different rate than the discount rate. The discount rates increase from 0% to 5% in steps of 2.5 percentage points. The resulting carbon price trajectories are depicted in **Figure S3** and are in line with the values presented in Strefler et al. (2021). Though we present results for only one discount rate (2.5%), we also analyzed the net present value of each scenario under five different assumed discount rates (**Figure S4**).

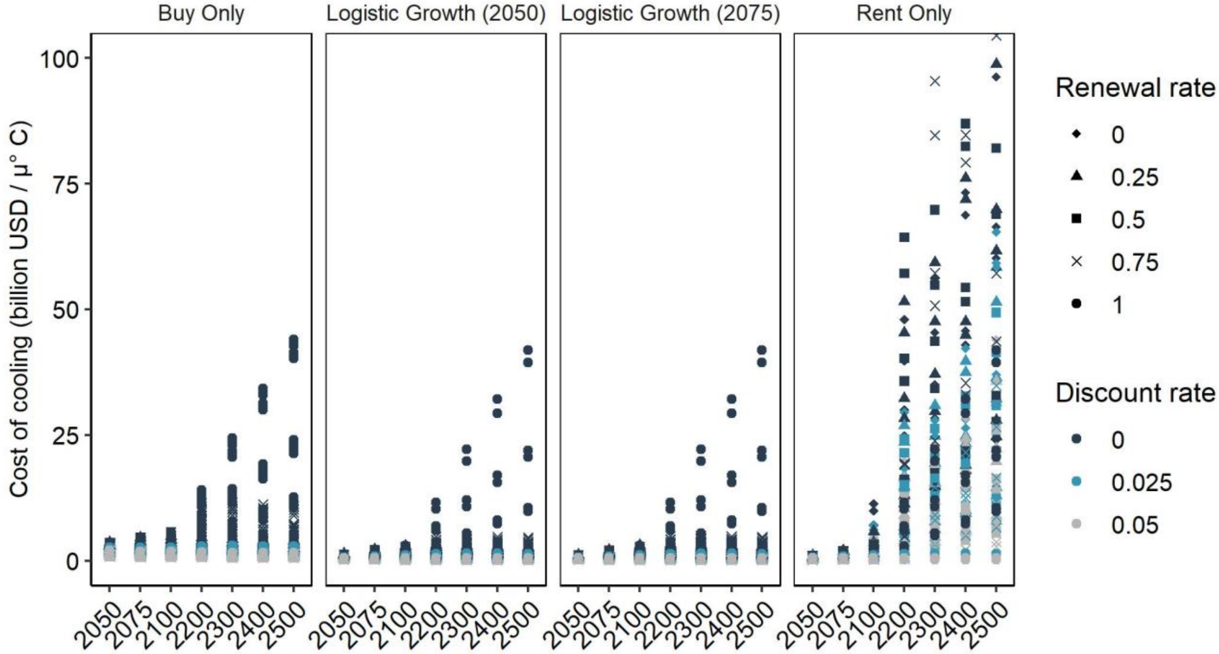

Figure S4: Net present cost of implementing a performance-based practice (y-axis) vs. the resulting temperature reduction from baseline (x-axis) was similarly sensitive to the rent vs. buy transition trajectories across all discount rates analyzed, including 0 (darkest blue), 0.025 (teal), and 0.05 (grey).

Regarding the payment policy, we differentiate between two policy cases: *Results-Based Payments* (not presented here) and *Practice-Based Payments*. In the case of *Practice-Based Payments*, the landowner receives a payment per hectare to implement a certain practice. Although those payments are fixed over time, land managers receive a per hectare payment even if the soil is no longer accruing carbon. This policy avoids the reversal of the carbon-removal practice once the soil has reached its steady state in terms of carbon stock. The three per-hectare payment amounts are assumed to be $50, $125, and $200. In the case of *Results-Based Payments*, payments to the landowner are based on the amount of CO_2 sequestered. In any case, the landowner is compensated for carbon accrued and does not need to pay in the case of carbon release. The result-based CO_2e also assume that carbon released gets immediately stored in geologic carbon. That is, all the negative flows from land are stored via DACS.

4 Decarbonization baselines

We present in the main text values for a low-emissions world as projected by Shared Socioeconomic Pathway 1 (SSP1-2.6), but also analyzed results for a moderate emissions world (SSP2-4.5). The temperature response of each rent-to-buy transition pathways is given in **Figure S5** for temperature baselines from both a moderate future shared socioeconomic pathway (SSP2 - 4.5) and a strong decarbonization pathway (SSP1 - 2.6). In every case, warming reductions from baseline are greater under SSP1 - 2.6, emphasizing the importance of combining *both* decarbonization and CDR strategies.

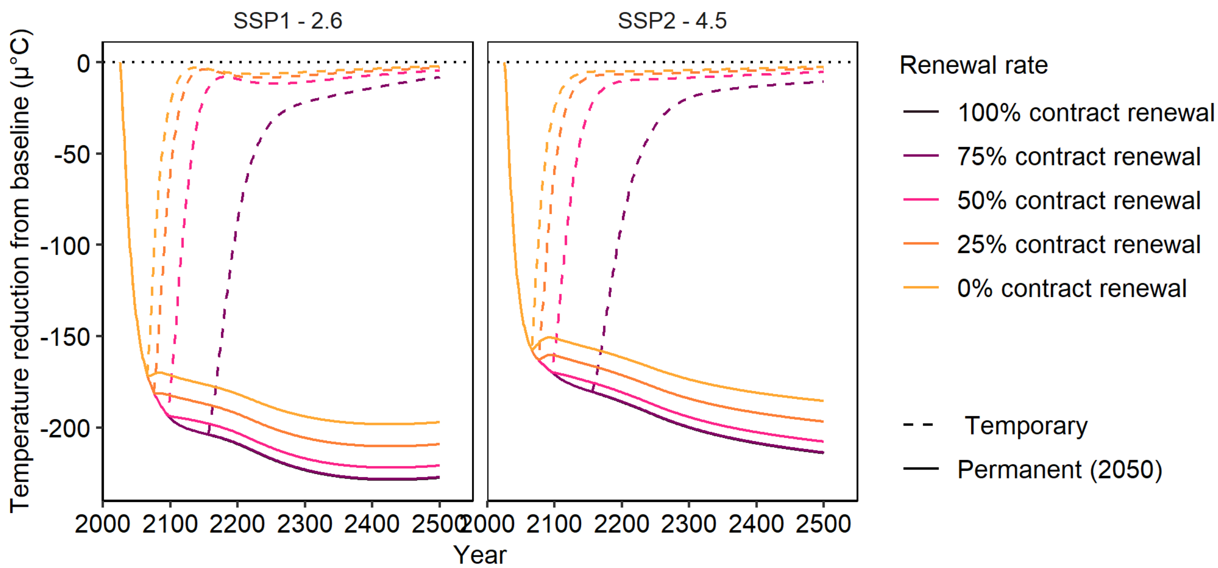

Figure S5: Comparison of warming reduction relative to baseline (SSP 1 - 2.6 , left and SSP2 - 4.5, right; y-axis) over time (x-axis) for 10 year contracts. The temporary “rent only” scenario is shown in dashed lines, with the permanent storage “buy only” given in solid lines. Five contract maintenance experiments, each representing a different contract renewal and thus initial CO_2 removal rate, are represented for the rent or buy scenario. The experiments represent a range of removal rates versus storage maintenance: high initial removal rates and no maintenance for 0% contract renewals (yellow), 25% contract renewals (orange), 50% contract renewals (pink), 75% contract renewals (magenta), and maintenance of storage only with no shifting contracts in the 100% contract renewal experiment (black).

5 Contract lengths

Maintenance of temporary carbon storage through cropland management can be simulated by extending contracts two ways: renewal rate of finite contracts or the duration of the contract. Because both mechanisms can increase or decrease storage maintenance, we chose renewal rates as a primary example to demonstrate a range of storage durations. Increasing contract lengths has the same principle effect on carbon accrual in patches, temperature impacts, and net present values. **Figure S6** shows the factorial effect of renewal rates and contract lengths on temperature reduction from both baseline emissions pathways.

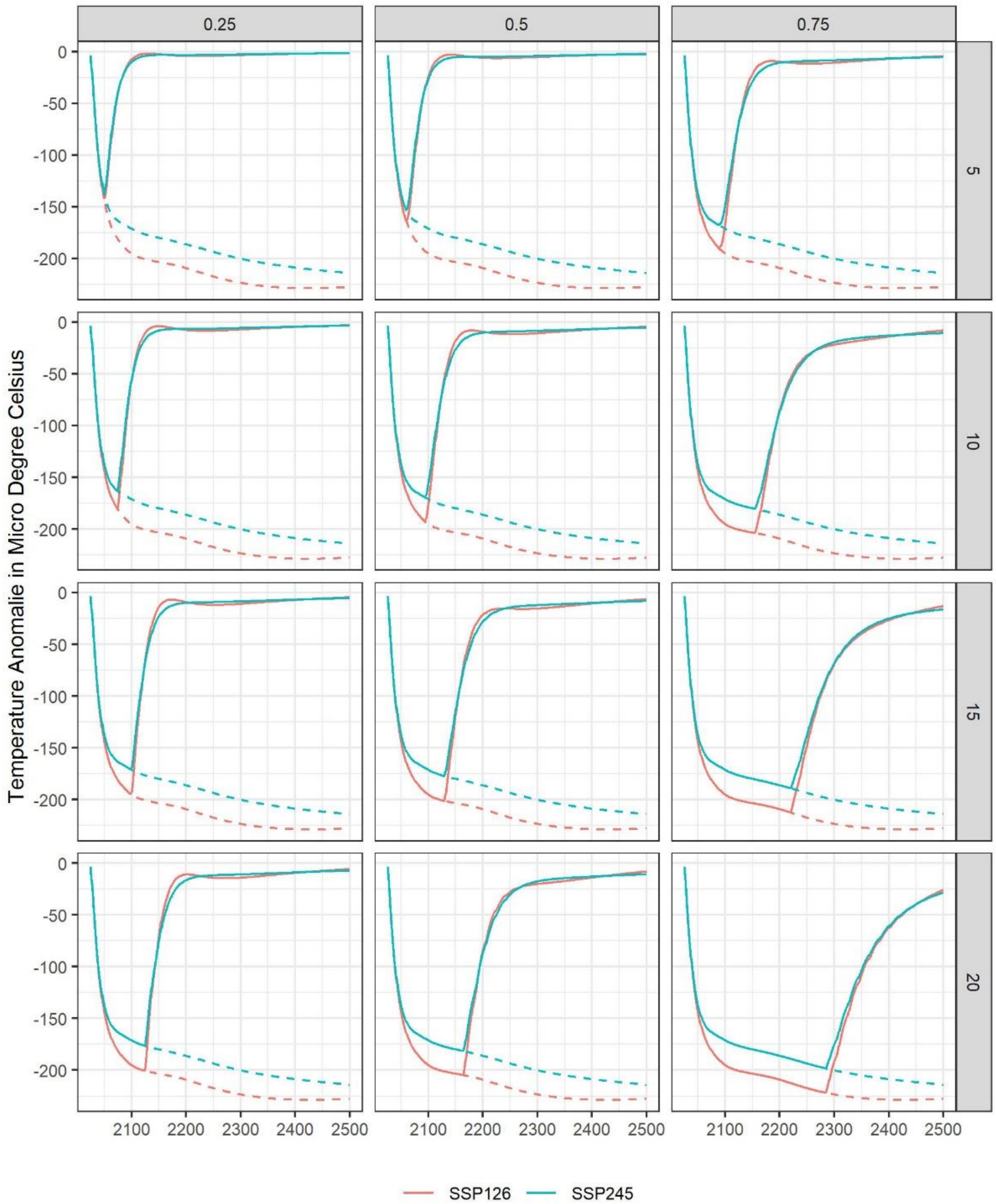

Figure S6: Temperature reductions from baseline scenarios (SSP1 -2.6, blue and SSP2 -4.5, red) depend on how long carbon can be maintained in temporary storage, for “rent only” cases, when no permanent storage is available. Temporary storage can be maintained through increasing renewal rates, given as fractions for each column increasing from 25% renewal on the left to 75% renewal on the right, or through increasing contract lengths. Contract lengths increase from 5 years in the top row to 20 years in the bottom row. Dashed lines indicate 100% renewal rate for continuously implemented projects, while solid lines indicate the temperature reduction for the combination of renewal rate and contract length.