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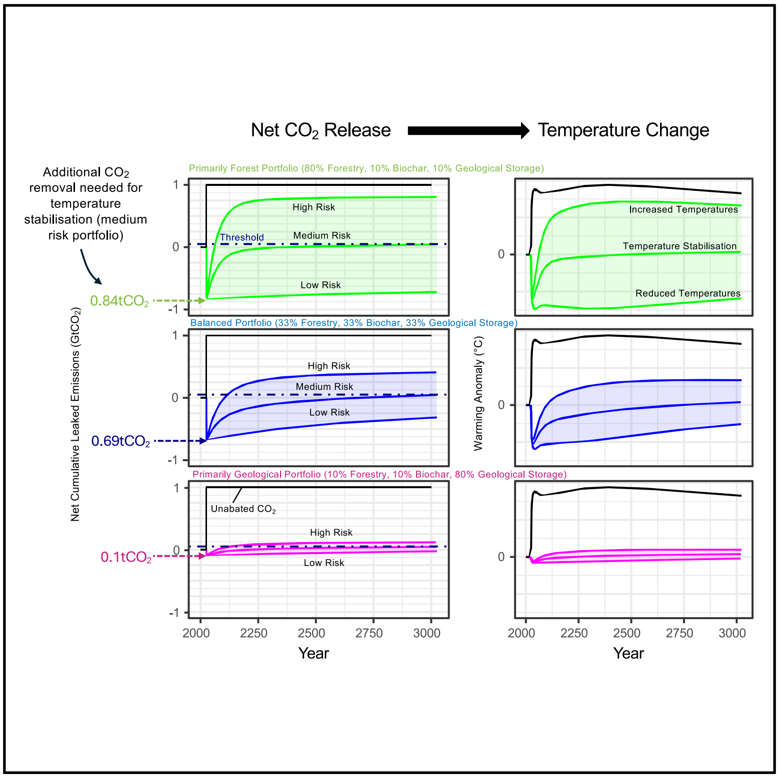
Carbon storage portfolios for the transition to net zero

Graphical abstract



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In brief

Companies and countries are investing billions in carbon removal projects to meet net-zero targets but without much insight into how their investments will stabilize global temperatures. This study shows that mixing risky projects (like forests that can burn) with low-risk ones (like underground storage) in carefully designed portfolios can support climate goals. However, portfolios dominated by high-risk projects require impractically large amounts of extra carbon removal, making them ineffective for long-term temperature stabilization.

Highlights

- Collective buffer pooling reduces project risk and stabilizes temperatures
- Moderate-risk portfolios (retains >50%) stabilize temperatures via2 tCO$_2$ per offset
- High-risk portfolios (retains <10%) are ineffective for temperature goals
- Carbon markets can support a broader range of carbon storage options

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Carbon storage portfolios for the transition to net zero

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CONTEXT & SCALE To achieve global temperature stabilization goals, such as those set out in the Paris Agreement, current projections suggest that between 7 and 16 gigatons of CO_2 removal annually could be required by the second half of the century. Relative to what is required, there are currently significant shortages, particularly for geological storage options. Carbon removal projects have different risk characteristics in terms of releasing CO_2 back into the atmosphere. Natural climate solutions like forestry face reversal risks from wildfires, droughts, and land-use changes, while technologically focused projects such as direct air capture with geological storage offer greater permanence but face delivery risks around scalability, cost, and technological maturity. Additionally, costs vary by orders of magnitude between forestry offsets and engineered removal technologies.

The development of carbon dioxide removal (CDR) today is constrained by these dual challenges of risk and cost differentials, compounded by limited societal willingness to pay premium prices for higher-permanence solutions. Most current carbon markets treat different removal approaches as near fungible substitutes despite their fundamentally different risk characteristics. In this paper, we develop a portfolio approach to manage carbon storage project risks, with the potential to select CDR options available today, while maintaining the ability to stabilize temperatures over multi-century periods through “collective” buffer pools. These risk models work on similar principles to insurance, where a small number of payouts maintain a relatively stable overall market.

SUMMARY

Net-zero targets are widely adopted by companies and countries worldwide. To achieve these goals, more companies are investing in diverse carbon removal portfolios. This study develops a new risk management framework that combines forestry, biochar, and geological storage offsets into portfolios that could stabilize global temperatures over multi-century time periods. We find that if a carbon storage portfolio reaches an equilibrium state of CO_2 stored, it can be leveraged to stabilize global temperatures by increasing the size of the portfolio relative to the amount of removal claimed. For moderate-risk primarily forestry portfolios retaining 0.75–0.55 tCO_2 of the 1 tCO_2 stored, an additional 0.30–0.80 tCO_2 removal is needed to offset re-releases over 1,000 years. High-risk portfolios retaining only 0.10 tCO_2 require over 9 tCO_2 additional removal. Portfolios that are predicted to re-release almost all CO_2 cannot be leveraged and are ineffective at meeting temperature stabilization goals. These findings have implications for policy and corporate climate action.

INTRODUCTION

To meet the Paris Agreement goal of limiting warming to well below 2°C and pursuing 1.5°C, a balance between anthropogenic emissions and removals is needed to limit the accumulation of greenhouse gases (GHGs) in the atmosphere and resultant rising temperatures.[1] According to Smith et al., achieving net-zero emissions could require between 6.8 and 16 gigatonnes (Gt) of CDR annually, with even larger amounts needed later in the century.[2] However, the portfolio of CDR options used to

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meet this target may not fully substitute for emission reductions due to issues such as impermanence, biogeophysical effects, and impacts from non-CO_2 GHGs.[3] This paper evaluates if removing more CO_2 than initially claimed, along with risk ("collective buffer") pooling strategies, can mitigate the challenges of impermanence exclusively.

Owing to the current limited supply of durable or permanent CDR options, both buyers and sellers are increasingly using portfolios of CDR options to support corporate climate claims.[4–7] The initial composition of a portfolio will vary by region-specific biogeophysical constraints, market dynamics, and public policy.[8,9] However, to sustain long-term temperature goals, all CDR portfolios compensating for ongoing fossil fuel emissions must transition from higher-risk storage (e.g., biological) to more permanent geological storage by net zero.[10] In any case, emission reductions should be prioritized.[11]

To ensure the credible use of higher-risk CDR, policies and companies must show that their CDR portfolios deliver climate impacts comparable to emission reductions in stabilizing temperatures. Incentives for CDR today focus on biological CDR through market-based, public procurement and fiscal mechanisms,[12] within which liability for stored CO_2 is managed either ex-ante or ex-post. In the ex-ante approach, additional CO_2 is stored as a precaution to cover potential future releases (e.g., California ETS). The ex-post approach involves storing extra CO_2 or buying additional carbon credits if it is later released (e.g., EU ETS).[12]

The most common risk management approach involves using ex-ante buffer accounts or pools, which provide scheme-wide insurance against unexpected reversal.[12] Each participant must allocate a portion of their carbon credits in excess of their emissions to the buffer account. The liability for potential re-release is distributed among all participants based on the size of their individual offset accounts.

However, actuarial analysis suggests that buffer pools are currently severely undercapitalized relative to their risks over a 100-year period.[13,14] A key issue for policymakers has been in determining if and how much additional CO_2 removal could improve the fungibility of CDR with an emission reduction, producing a comparable impact on stabilizing atmospheric CO_2 concentrations and temperature change over a nominal period. Without effective risk management, policies that rely on CDR via the compliance or voluntary carbon markets may substantially overestimate CDR's long-term impact on limiting global warming.

This paper presents a framework to quantify the additional CO_2 removal needed to keep temperatures stable over multi-century time periods for various storage portfolios. Building on research on CDR effectiveness[15,16] and the costs of permanent CDR,[9] it assesses current risk management approaches in carbon markets[13,14,17] and contributes to the broader debate on carbon accounting for carbon offsets.[18–23]

This paper first presents a risk management framework to evaluate net cumulative leaked CO_2 from CDR storage portfolios. Next, we calculate the extra storage needed to reduce net cumulative leaked CO_2 below an established cumulative leakage threshold. We then demonstrate the impact of this approach on global temperatures using a reduced-complexity climate model.

RESULTS

Measuring and managing the climate impact of carbon storage options

In this section, we outline the framework for assessing CDR storage options by considering the impact of storing 1 tonne of CO_2 to offset the emissions of 1 tonne of CO_2.

A perfect store of 1 tonne of CO_2, occurring synchronously with the emission, fully compensates for the atmospheric perturbation over all time (in effect the perturbation never occurs). However, if the storage is imperfect and a fraction is later re-released, either in a single year or over decades, how should the purchased offset change to compensate for both the emission itself and the risk of stored CO_2 re-release? How can buyers differentiate between additional CO_2 removal to compensate for risk and making net negative claims?

All carbon storage types are vulnerable to some risk of reversal, such as leakage from geological storage or fire damage to forestry storage. While a single project may experience a total release of stored CO_2 at a given time, this typically represents only a small fraction of the total anthropogenic CO_2 stock being stored in a given year. This is similar to property insurance markets anticipating a subset of insured properties claiming payouts annually, whereby the overall system remains robust as long as the average number of incidents is low relative to the total number of policies. In contrast to property insurance markets, CDR projects at higher risk of re-release (or requiring payouts by insurance), such as tropical forests, can be subsequently associated with more rapid regrowth (and therefore recuperation of these carbon losses, subject to the land remaining available for the CDR activity to continue).[8]

Given this understanding, we established a threshold, approximating the net cumulative leakage of CO_2 for a CO_2 storage portfolio, which would have a negligible impact on global temperature change over time, and assuming land- or ocean-based removals are always entirely additional to any natural response to past emissions already occurring on those systems. This threshold sets a maximum released fraction for stored CO_2 units. If exceeded, it would indicate an ineffective solution to limiting the accumulation of CO_2 in the atmosphere and would thus result in higher temperatures.

In Figure 1A, we illustrate an example threshold for net cumulative leakage (navy line), which corresponds to a limit of 5% (0.05 tonnes) per tonne of CO_2 removed over a 1,000-year period. The 5% threshold is a placeholder to populate the model, as the associated CO_2 release had minimal long-term impact on CO_2 concentrations (see Figure 1B). In practice, such thresholds would likely be set through policy or consultation processes—similarly to how central banks adjust interest rates by committee. For instance, the EU and UK are considering a 200-year benchmark for permanent storage, which may be extended as longer-term solutions scale.[24,25] Low-risk-of-re-release CO_2 storage could comply with the threshold as long as its leakage (orange line), a function of its risk of re-release, remains below the specified threshold. While this initially high threshold could align with

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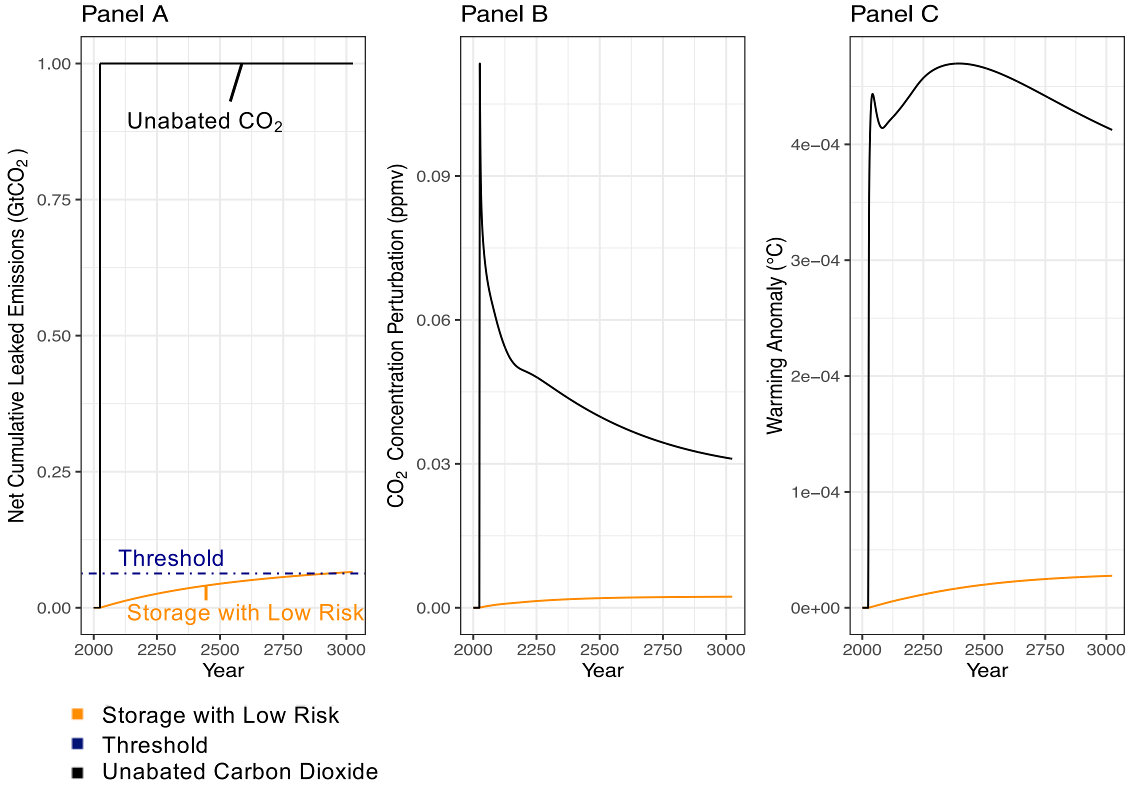

Figure 1. Impact of low-risk CO_2 storage leakage on atmospheric concentrations and global temperature

(A–C) Impact of emission instantaneously compensated for with low-risk storage on net cumulative leaked CO_2 (A), atmospheric CO_2 concentrations (B), and global temperature change (C). At year zero, 100% of the CO_2 claimed as removed is registered as stored; then, it is released over time through biochar decay, geological leakage, or the loss of a fraction of the global forest stock to fire each year. As CO_2 is re-emitted, it accumulates in the atmosphere (B), with some absorbed by the biosphere, oceans, and geosphere. The resulting warming is shown in (C). We set a low-risk threshold to limit the amount of risk and subsequent CO_2 leakage from storage over time to minimize warming. In this example, CO_2 storage can release a maximum of 0.05 cumulative tonnes of CO_2 leaked over 1,000 years. SSP scenarios are used to provide background information on the state of the climate system. We use SSP 1–2.6 as an example, which limits global warming to around 1.8°C (1.3°C–2.4°C) by the end of the century. The purpose of this figure is to show that if net cumulative leaked emissions can be managed below an appropriate threshold, then the climate impacts in (B) and (C) are likely to be stable.

relatively higher-risk-of-re-release CO_2 storage options currently available on the offset market, it should not be considered static. If society's tolerance for stored CO_2 re-release changes or lower-risk CO_2 storage projects become available, the threshold could transition downward over time (e.g., 0.5%, 0%).

Figures 1B and 1C depict the impact of net cumulative CO_2 emissions (from Figure 1A) on atmospheric CO₂ concentration perturbation and global temperature change, respectively, over time using a reduced-complexity climate model (FaIR — described in Note S4 of the supplemental information). The model allows inputs of GHG and short-lived climate forcer emissions to estimate global mean atmospheric GHG concentrations, radiative forcing, and temperature anomalies. It is calibrated against full complexity CIMP6 earth system models, including global average relationships for carbon cycle response timescales, thermal cycle response timescales, as well as global average behaviors of other non-CO_2 climate forces. The black line in Figure 1B shows that unabated emissions decline rapidly in the early decades due to quick uptake by the biosphere and shallow ocean, followed by a millennium-scale tail as slower uptake processes in the deep ocean and geosphere take effect. Figures 1B and 1C are not a part of the framework themselves but are there to demonstrate the importance of focusing on net cumulative leaked CO_2 (Figure 1A).

CO_2 released from storage is emitted immediately when a leakage event occurs and decays. Over time, the impact of this CO_2 release on atmospheric concentrations diminishes as it is reabsorbed by non-atmospheric carbon pools. As a result, the overall atmospheric CO_2 response depends on both the leakage rate and the background state of the carbon cycle. FaIR is an impulse response model formulated with four global carbon cycle pools and three thermal boxes. Non-linear feedbacks in the carbon cycle response to rising temperature and cumulative emissions are included through a single adjustment to carbon cycle response timescales and are described in full in Leach et al.[26,27] In this analysis, we use the shared socioeconomic pathways (SSPs), with SSP1-2.6 serving as the default background state for the carbon cycle. SSP1-2.6 represents a scenario where the world follows a sustainable development path (SSP1), and efforts to mitigate climate change are aggressive enough to limit global warming to around 1.8°C (1.3°C–2.4°C) by the end of the century.

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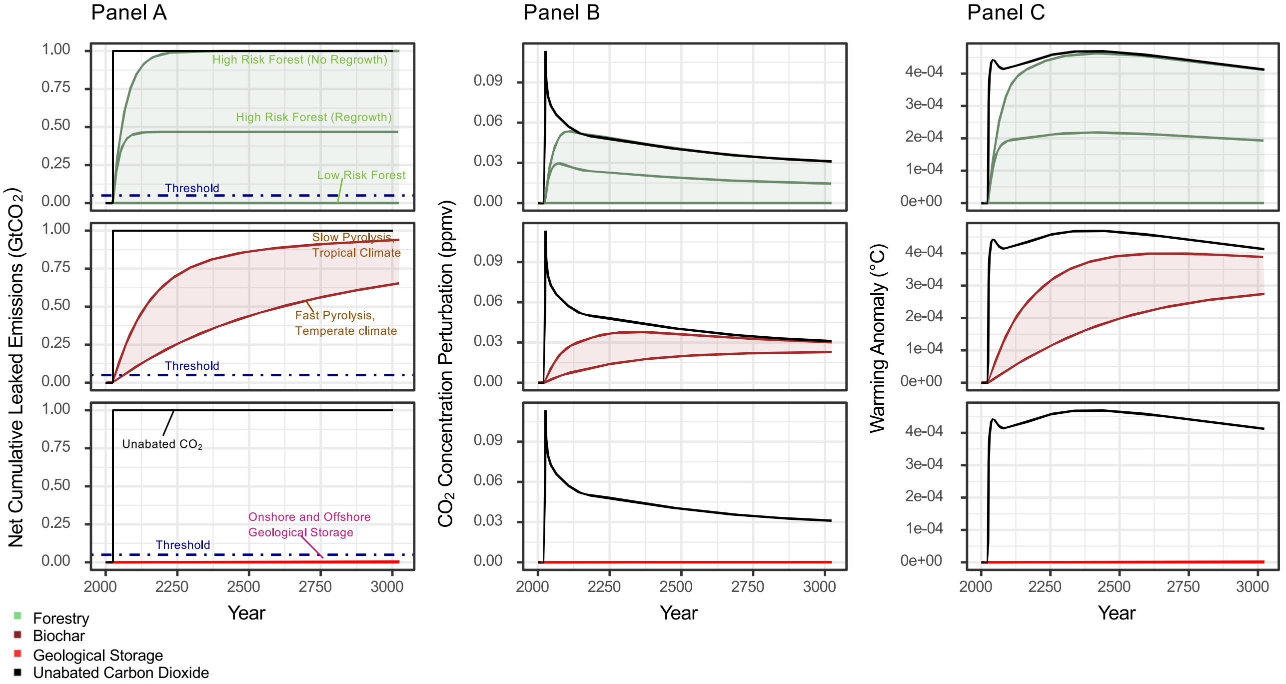

Figure 2. Comparative performance of carbon storage types on climate outcomes

(A–C) Impact of emission instantaneously compensated for with each carbon storage type, with (A) showing the effect on net cumulative CO_2 leakage, (B) on atmospheric CO_2 concentrations, and (C) on global temperature change. Risk threshold: 0.05 cumulative tonnes CO_2 leaked over 1,000 years. SSP scenario: SSP 1–2.6.

Biological carbon storage alone is unlikely to stabilize global temperatures at any timescale

In this section, we apply the framework described earlier to test forestry, biochar, and geological storage projects against the threshold by using risk models.

Figure 2 illustrates the range of impacts on net cumulative leaked CO_2 (Figure 2A), atmospheric CO_2 concentrations (Figure 2B), and global temperature change (Figure 2C) from a range of forestry, biochar, and geological storage projects over 1,000 years, accounting for the risk of release when offsetting a 1-tonne CO_2 emission by storing 1 tonne of CO_2. Each color band represents a full range of risks of reversal outcomes, with bold lines showing the highest and lowest estimates for each storage type and the shaded area between them capturing moderate scenarios. Forestry data are drawn from the LANDFIRE program, covering tropical, sub-tropical, temperate, and boreal climates. Biochar decay is modeled using a two-pool exponential approach based on data from Woolf et al. (2021),[28] varying by pyrolysis temperature (slow: 350°C–450°C, medium: 450°C–600°C, fast: ≥600°C) and soil temperature (from 10.9°C to 25°C), with decay rates projected over 1,000 years. Geological storage forms part of a value chain in which CO_2 is captured at point source or from the air. Onshore and offshore geological CO_2 storage dynamics are assessed using a storage security calculator. Further details and scenarios are in the supplemental information in Figures S1–S3 and Table S1, with the highest- and lowest-risk scenarios described below.

- Forestry: the lowest risk is a forest that never catches fire (lower green line), the highest risk is a tropical forest burned every 46 years with 60% never regrowing with each fire (upper green line) until the amount of CO_2 stored asymptotically approaches zero, and mid-risk is a tropical forest that regrows linearly over 40 years after each fire (middle green line).
- Biochar: the highest decay rate (upper brown line) is from biochar using slow pyrolysis in a tropical environment, while the lowest decay rate (lower brown line) is from biochar using fast pyrolysis in a temperate environment.
- Geological storage: the range from an unregulated onshore project (upper red line) to a highly regulated offshore project (lower red line) post-injection is minimal.

The impacts of each storage type on CO_2 concentrations and temperature change vary significantly across scenarios, but all lower and delay peak global temperature increases (Figure 2C), since all reduce atmospheric CO_2 for a period of time (Figure 2B). In a high-risk forestry scenario, CO_2 storage could delay peak atmospheric CO_2 concentrations by a minimum of 80 years (Figure 2B), with a relative change of 0.053 parts per million by volume (ppmv) at the top of green plume, relative to a release of 1 tonne of CO_2 (tCO_2) in year 0 (black line). However, after this point, CO_2 concentrations are in fact higher than had the emission not been offset, since the carbon cycle is perturbed and less capable of re-absorbing the leaked CO_2 at this time. By around year 200, all the stored CO_2 has been re-released.

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Table 1. Assumptions for carbon storage offset portfolios

Storage type	Primarily forestry portfolio	Balanced portfolio	Primarily geological storage portfolio
Forestry (%)	80%	33%	10%
Biochar (%)	10%	33%	10%
Geological storage (%)	10%	33%	80%

In the mid-risk scenario (with regrowth), peak CO_2 concentration changes are limited to 0.03 ppmv around 100 years (Figure 2B) after the initial storage takes place (middle green line), and they lead to a long-term benefit in warming below the no offset scenario. As more forest is lost, the area available for regrowth increases, causing annual fire losses to balance with regrowth by year 105, stabilizing 53% of the CO_2 initially stored over a 1,000-year period. The lowest-risk forestry storage—such as co-locating a project with an old-growth forest that has not burned—could delay the peak indefinitely by leaking no CO_2 over 1,000 years, meeting the threshold shown in navy defined in Figure 1.

Biochar carbon storage delays the change in peak CO_2 concentrations by a minimum of 250 years (Figure 2B) in a fast decay biochar scenario to 0.038 ppmv. In the slower decay scenario, it delays the change in peak atmospheric CO_2 perturbation to 0.023 ppmv in year 1000. Biochar is unable to meet the cumulative leakage threshold.

In contrast, geological storage effectively reduces the peak atmospheric CO_2 levels indefinitely (Figure 2B) and well below the cumulative leakage threshold. Furthermore, geological storage shows the highest likelihood of stabilizing temperatures over the 1,000-year period (Figure 2C), compared with warming anomaly of between 0.0002°C and 0.0004°C for both biochar and mid- to higher-risk forestry by year 1000. Hence, geological storage has negligible change in warming anomaly over the 1,000-year interval.

Diversified portfolios reduce CO_2 leakage but are unlikely to stabilize global temperatures

When a single storage type fails to meet the threshold (e.g., biochar) or there is a shortage (e.g., geological storage), users can consider CO_2 storage portfolio offsets. In this section, we create and test a mix of different storage types to collectively offset 1 tonne of CO_2.

CO_2 storage portfolio offsets use low-risk storage types, like geological storage, to mitigate the risks of higher-risk types, such as forestry, achieving a lower average risk of re-release in the portfolio. The concept of "prosets" has emerged, which progressively increases carbon allocation to geological storage, reaching 100% by the target net-zero date.[29] This strategy can also manage a declining threshold by placing more CO_2 in low-leakage geological storage. Additionally, Climeworks, a pioneer in direct air capture, now sells offset portfolios that include both biological and geological storage.[5] Rubicon Carbon actively manages its carbon portfolio of removals to

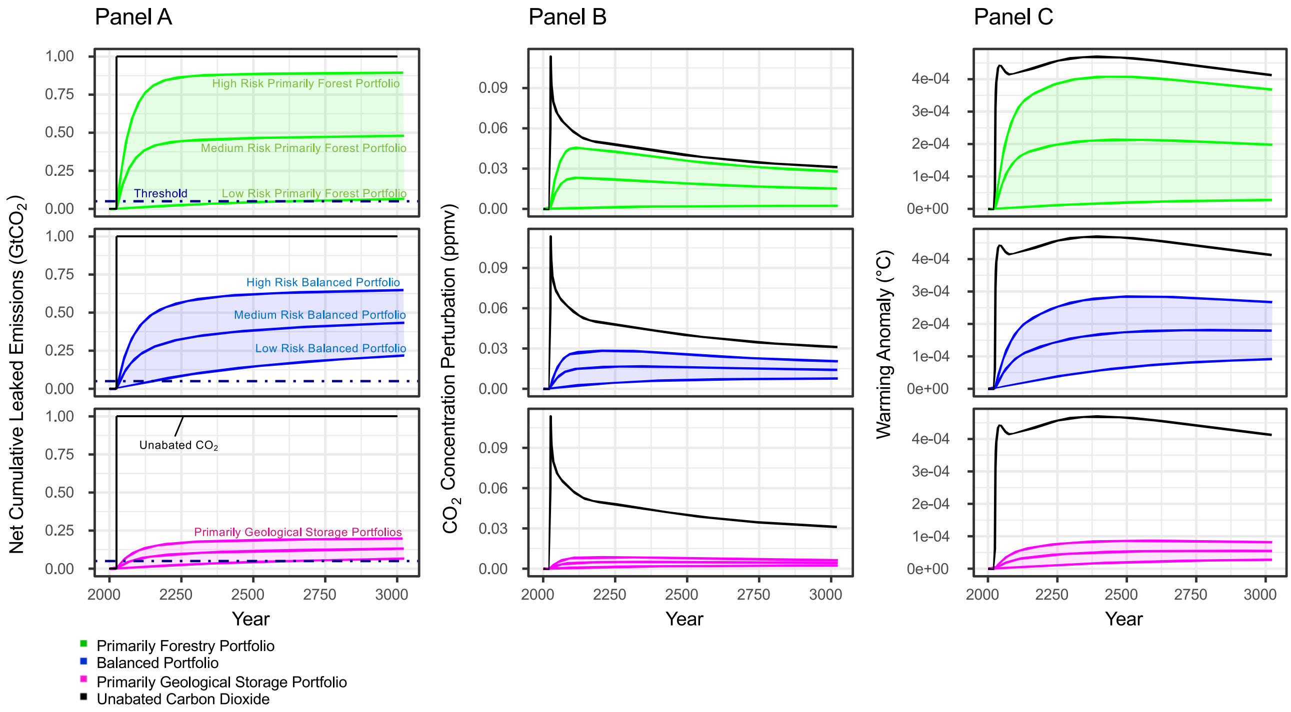

Figure 3. Comparative performance of carbon storage portfolios without forest regrowth

(A–C) Impact of emission instantaneously compensated with each carbon storage portfolio, with (A) showing the effect on net cumulative CO_2 leakage, (B) on atmospheric CO_2 concentrations, and (C) on global temperatures change, all *without* forest regrowth. Risk threshold: 0.05 cumulative tonnes CO_2 leaked over 1,000 years. SSP scenario: SSP 1–2.6.

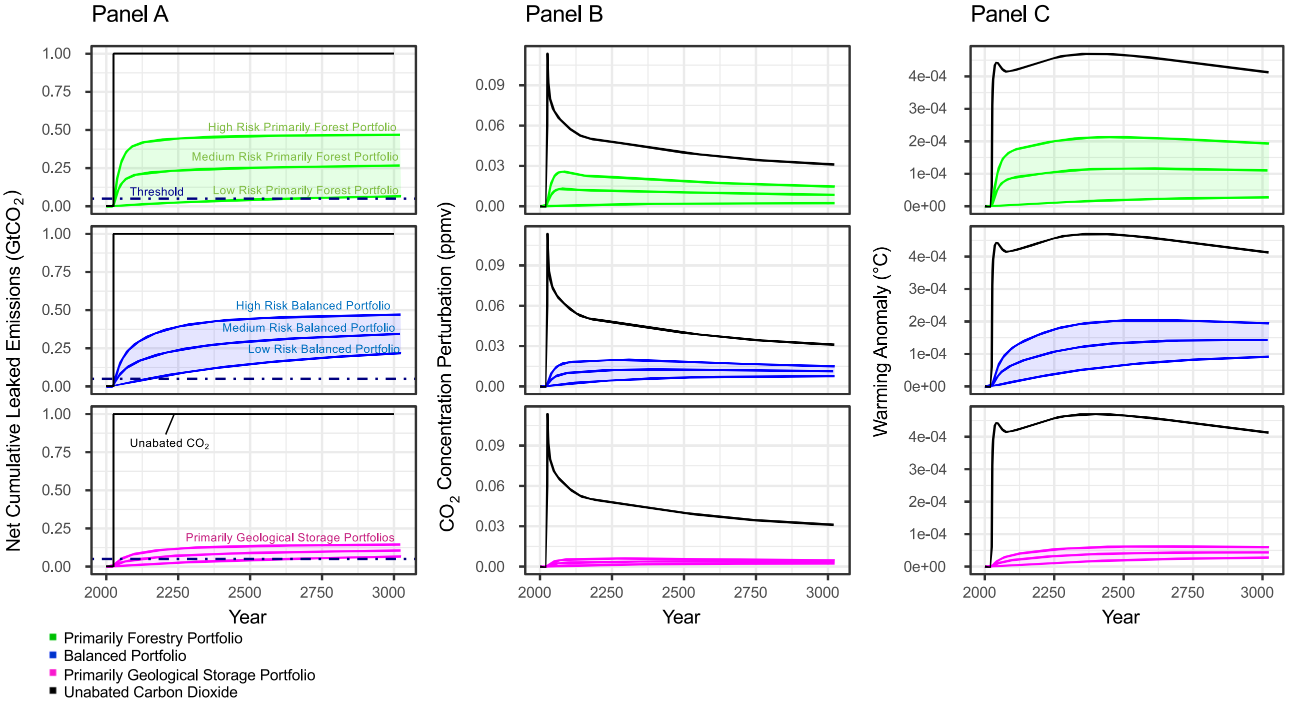

Figure 4. Comparative performance of carbon storage portfolios with forest regrowth

(A–C) Impact of emission instantaneously compensated with each carbon storage portfolio, with (A) showing the effect on net cumulative CO_2 leakage, (B) on atmospheric CO_2 concentrations, and (C) on global temperature change, all *with* forest regrowth. Risk threshold: 0.05 cumulative tonnes CO_2 leaked over 1,000 years. SSP scenario: SSP 1–2.6.

meet permanence and integrity requirements of buyers after the credit is sold.

Table 1 provides an overview of three example CO_2 storage portfolio offsets. Portfolios range from high forestry content to equal shares, down to low forestry levels. We provide an analysis of these portfolios, which assumes forests do not grow back in Figure 3 and that they do grow back in Figure 4. In the supplemental material, we also test a primarily biochar portfolio in Table S1.

After creating each CO_2 storage portfolio offset, the average risk of re-release is calculated based on the range between the highest and lowest re-release rates for each individual storage type (represented by the middle colored lines in Figures 3 and 4). These averages are then used to estimate the average- or medium-risk release rate for the portfolio. Effectiveness for each CO_2 storage portfolio offset is determined by its ability to maintain an average risk of re-release (net cumulative leakage) below the specified threshold—in this case, 5% cumulative CO_2 leakage over 1,000 years.

All CO_2 storage portfolios in Figures 3 and 4 effectively lower and delay peak atmospheric CO_2 concentrations, compared with forestry and biochar storage alone. However, no portfolio keeps its average annual release rate below the threshold, and temperatures continue to rise. Note that the net cumulative leakage rate for the primarily geological storage portfolio still exceeds the threshold, due to the high leakage rates in the other two storage types.

When accounting for forest regrowth in Figure 4, the impact on atmospheric CO_2 concentrations is much lower, and the primarily forestry portfolio outperforms the balanced portfolio in the long run. This assumes that land-based offsets are truly additional to the passive uptake already occurring on the land and that the land can be protected over a very long period of time—meaning the CO_2 would not have been removed and stored without the project. However, these two portfolios of offsets are both found to be ineffective in meeting the threshold. In all three portfolios, to match the duration of CO_2 storage over timescales relevant to fossil CO_2 emissions, additional mitigation measures beyond procuring carbon storage portfolios are required.

Diversified portfolios that remove more CO_2 than they claim can stabilize global temperatures over centuries

One approach to mitigate the risk of CO_2 re-release undermining the credibility of an offset portfolio is to adjust the portfolio's CO_2 storage size to account for this future leakage risk. In this section, we test if and how much additional CO_2 removal could make the portfolios analyzed in the last section meet the threshold, adjusting portfolio size relative to risk of release. This approach compensates for the transient nature of certain CO_2 storage options, a common practice (e.g., buffer accounts).

Additional CO_2 storage would effectively scale up CO_2 storage portfolio offsets, reflecting the original fractions of each storage type. Consistent with previous examples, we start by assuming that one unit of CO_2 has been released and offset (net carbon = 0) at t = 0, before gradual leakage results in its re-release into the atmosphere. To compensate for this, additional CO_2 removal occurs at time t = 0. For example, a 10% risk adjustment assumes

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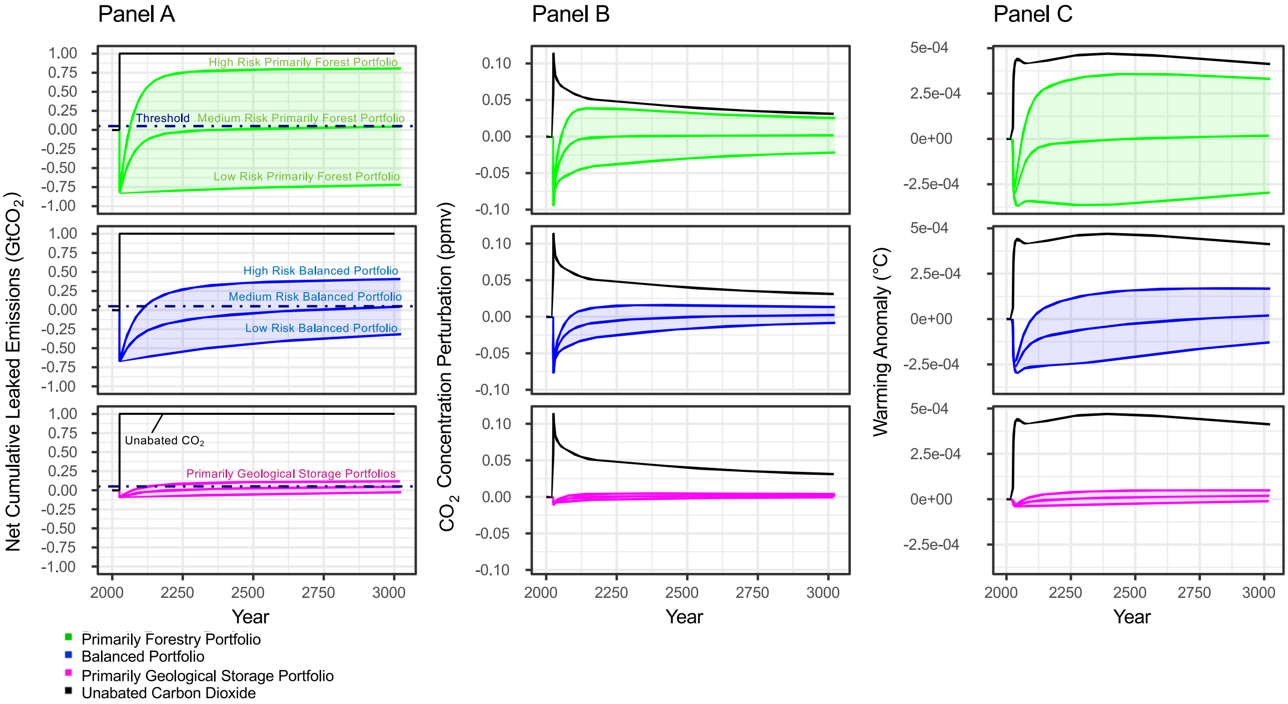

Figure 5. Climate impacts of risk-adjusted carbon storage portfolios to meet threshold without forest regrowth

(A–C) Impact of emissions instantaneously compensated by each risk-adjusted carbon storage portfolio, with (A) showing the effect on net cumulative CO_2 leakage, (B) on atmospheric CO_2 concentrations, and (C) on global temperature change, all *without* forest regrowth. Risk threshold: 0.05 cumulative tonnes CO_2 leaked over 1,000 years. SSP scenario: SSP 1–2.6. For the no-regrowth scenario, the required CO_2 storage is 1.84 tCO_2 per tonne offset for the primarily forestry portfolio (84% additional), 1.69 tCO_2 for the balanced portfolio (69% additional), and 1.1 tCO_2 for the primarily geological portfolio (10% additional). Reducing the highest-risk portfolios (top line in each band) below the threshold would require up to 900% more storage for the primarily forestry portfolio and 270% for the balanced portfolio.

that one unit of CO_2 has been offset with 1.10 units, resulting in a net CO_2 emission of -0.10 tCO_2 at $t = 0$. The rate of re-release is also increased to reflect the additional CO_2 stored (in this example by a factor of 1.10).

Figures 5 and 6 shows the risk-adjusted average re-release rates for the primarily geological, forestry, and balanced portfolios. Figure 5 illustrates the additional CO_2 removal required if the forest does not regrow, while Figure 6 shows the impact of linear forest regrowth over 40 years after each release.

The risk adjustment aims to reduce the average net cumulative CO_2 leakage from storage, bringing it below the cumulative leakage threshold of 5% over 1,000 years. Making these adjustments for the portfolio offsets in Table 1, for the primarily forestry portfolio, the average necessary total CO_2 stored per tonne of sold CO_2 offset is 1.84 tCO_2 (assuming no regrowth) or 1.30 tCO_2 per tonne offset (assuming regrowth over 40 years). For the balanced portfolio, the necessary total CO_2 storage is 1.69 tCO_2 per tonne CO_2 offset sold (assuming no regrowth) and 1.45 tCO_2 per tonne offset sold (assuming regrowth). Across these offset portfolios this corresponds to additional CO_2 storage requirements of 84%, 30%, 69%, and 45%, respectively. The adjustment for the primarily geological portfolio is between 10% (assuming no regrowth) and 6% (assuming regrowth).

While the risk adjustment to the average primarily forestry and balanced portfolios leads to a greater temporary immediate change in global temperature (Figure 5C), compared with geological portfolio, the spread of risk within these portfolios is significant (as shown by the green and blue shaded bands). To bring the highest-risk portfolios (upper line in each band) in Figure 5 below the threshold for the primarily forestry portfolio and the balanced portfolio, up to an additional 900% and 270% storage would be required, respectively. The primarily geological portfolio requires an additional 20% storage. For the portfolios with regrowth, to get the highest-risk scenarios below the threshold, both the primarily forest and balanced portfolios would need additional CO_2 removal of 80% (1.8 tCO_2). The primarily geological portfolio would require 10% CO_2 removal.

Climate change can create Earth system feedbacks by triggering processes like increased wildfires, thawing permafrost, and changes in vegetation, all of which can release more CO_2 into the atmosphere. These feedbacks amplify warming, creating a self-reinforcing loop that accelerates climate change. As a result, the carbon cycle is altered, with more CO_2 being released from natural sources, making it harder to balance emissions and maintain climate stability.

To capture this key sensitivity, we re-run the portfolios in Figure 5 under a variety of warming scenarios in Figure 7. In SSP1-1.9, global warming is limited to about 1.4°C (1.0°C–1.8°C) by 2100. SSP1-2.6 results in 1.8°C (1.3°C–2.4°C) of warming by the end of the century. In SSP2-4.5, warming

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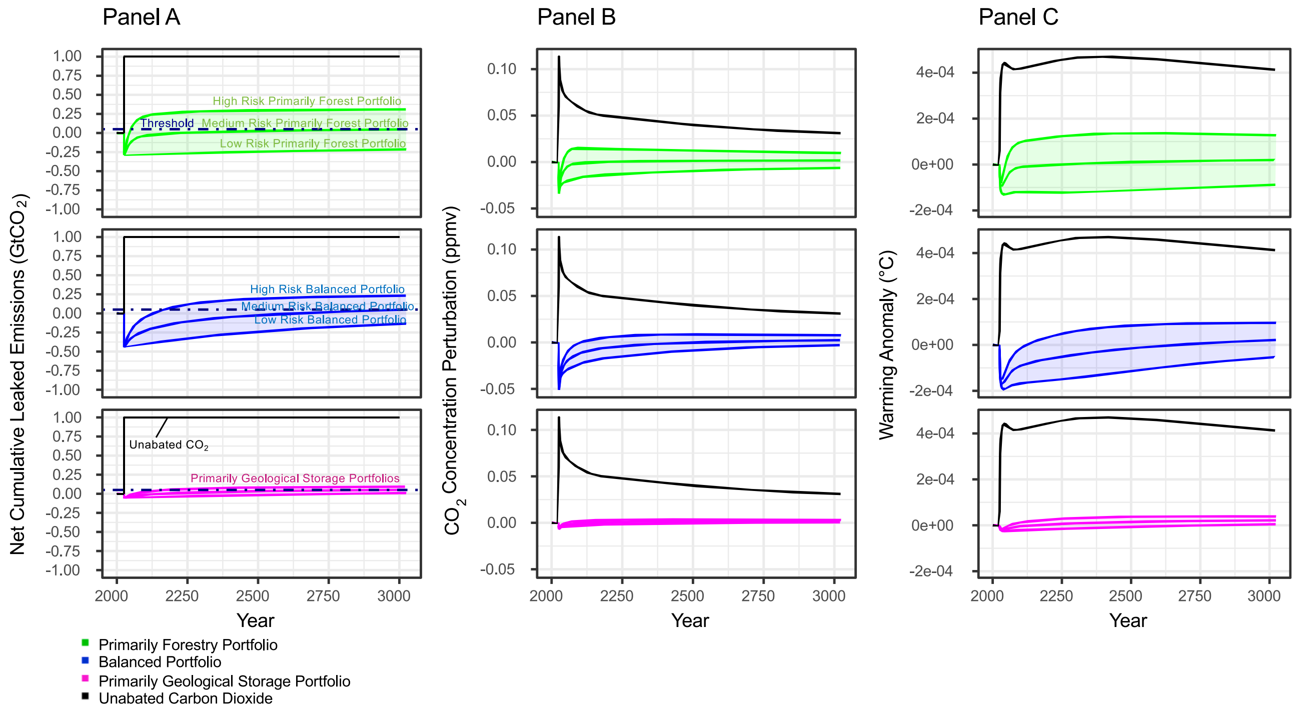

Figure 6. Climate impacts of risk-adjusted carbon storage portfolios to meet threshold with forest regrowth

(A–C) Impact of emissions instantaneously compensated by each risk-adjusted carbon storage portfolio, with (A) showing the effect on net cumulative CO_2 leakage, (B) on atmospheric CO_2 concentrations, and (C) on global temperatures, all *with* forest regrowth. Risk threshold: 0.05 cumulative tonnes CO_2 leaked over 1,000 years. SSP scenario: SSP 1–2.6. For the regrowth scenario (over 40 years), the required CO_2 storage is 1.30 tCO_2 per tonne offset for the primarily forestry portfolio (30% additional), 1.45 tCO_2 for the balanced portfolio (45% additional), and 1.06 tCO_2 for the primarily geological portfolio (6% additional).

reaches approximately 2.7°C (2.1°C–3.5°C) by 2100. As temperatures increase, it is still possible for the portfolios to stabilize temperatures. However, temperature outcomes are more uncertain for higher-risk projects, and the FaIR model contains only a first-order representation of Earth system feedbacks. These include non-linear carbon cycle responses to the accumulation of CO_2 in the ocean and land biosphere carbon pools—and the aggregate response of the carbon cycle to increased surface temperatures—both of which reduce the strength of the carbon sinks over time. See description in Leach et al. and Millar et al. for further details.[26,27] In the context of this paper, we do not explore parameter sensitivities of the model, since the focus of this work is on portfolio design rather than geophysical modeling. Higher warming scenario, using all available SSPs, are in the Figure S4.

DISCUSSION

This study investigates if combinations of carbon storage options, structured as portfolios, can stabilize global temperatures in ways that individual storage methods cannot. These portfolios manage risk by removing more CO_2 than claimed, creating a collective buffer to compensate for potential future leakage. We assess their effectiveness by measuring net cumulative CO_2 leakage over a multi-century timescale.

Using an established reduced-complexity climate model, we show that high-risk portfolios can reduce their net cumulative CO_2 leakage by removing additional CO_2 and, under certain conditions, deliver temperature outcomes comparable to permanent storage. This included net cumulative leakage remaining below a prescribed threshold over the relevant policy time frame. As the net-zero date approaches, countries and companies could reduce the leakage threshold to zero to enhance the durability of their net-zero claims.[30] While temperature responses to CO_2 leakage are complex and uncertain over these timescales, the relationship between cumulative emissions and global temperature is well understood. For example, this climate model has previously been used to analyze the temperature impacts of different GHGs over centuries.[31] Here, we apply it to assess the relative temperature effects of various carbon storage portfolios, consistent with established practice.

We propose that policymakers adopt project-level risk assessments of net cumulative CO_2 leakage as a criterion for including storage options in carbon markets and policy instruments. By modeling long-term leakage, they can set quantitative thresholds aligned with temperature stabilization goals. Currently, for example, EU and UK CDR policy proposals target a 200-year storage duration, yet often assume permanence over these time frames without fully evaluating leakage risk.[24,25]

In the absence of a robust risk-based framework like the one proposed here, it will be difficult to assess the true climate impact of CDR policies. Our analysis shows that in some cases, such as a primarily forestry portfolio, the additional CO_2 removal required to compensate for risk is similar whether the timescale

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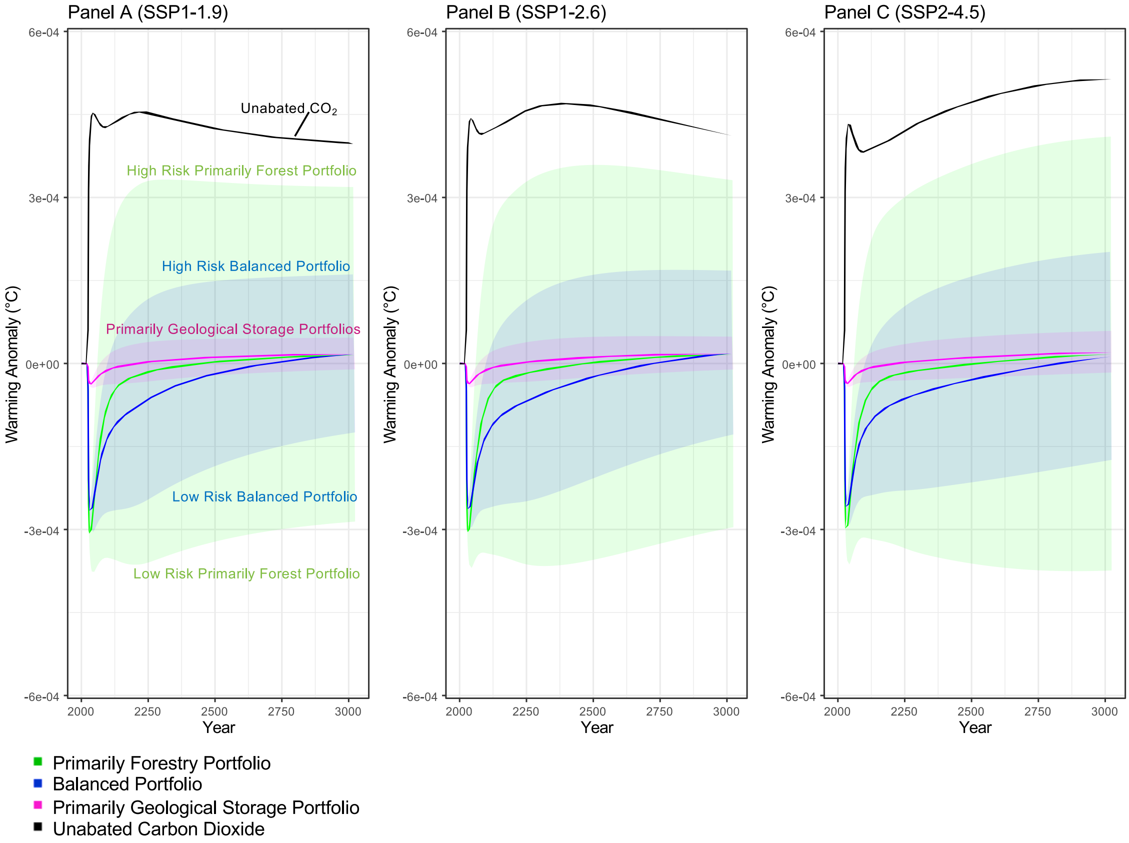

Figure 7. Temperature impacts of risk-adjusted carbon storage portfolios across SSP scenarios

Impact on global temperatures of emissions instantly offset by each risk-adjusted carbon storage portfolio (*without* forest regrowth) under different IPCC warming scenarios.

(A) Results for SSP1-1.9, 1.4°C (1.0°C–1.8°C) by 2100.

(B) Results for SSP1-2.6, 1.8°C (1.3°C–2.4°C) by 2100.

(C) Results for SSP2-4.5, with warming reaching approximately 2.7°C (2.1°C–3.5°C).

is 300 or 1,000 years. This suggests that additional CO_2 removal can be effective across extended time horizons.

In carbon markets globally, buffer accounts are the most common method for managing re-release risk, typically requiring 3% to 25% additional CO_2 removal.[12] Even in a portfolio comprising 90% impermanent storage (80% forestry, 10% biochar, and 10% geological), with no regrowth after forestry leakage, the average additional CO₂ required to limit cumulative leakage to under 5% over 1,000 years is 0.84 tCO_2 per 1 tCO_2 offset sold. A one-to-one buffer (2 tCO_2 stored per offset) would therefore be sufficient in most cases. In more vulnerable portfolios, such as those represented by the top green line in Figure 3, this requirement could exceed 900%. In all cases, the adjustment for leakage risk may be minor, compared with the adjustment for societal risk, such that support for maintaining impermanent carbon storage diminishes over time.

Global CDR is currently ~1,985 million tonnes of CO_2 ($MtCO_2$)/year, nearly all from land use and forestry (~1,983 $MtCO_2$/year), with only ~2 $MtCO_2$/year using geological storage and biochar.[32] Climate change can increase the risk of CO_2 being released from biological carbon storage, for example, higher wildfire risks and uncertainties in Earth system feedbacks. These risks are not captured in our analysis and can undermine the effectiveness of both past and future CO_2 storage projects. Buyers should avoid investing in storage projects already deemed high risk owing to future climate risks. By lowering the leakage threshold, this uncertainty can be addressed, with a threshold set at zero ensuring no leakage from any new anthropogenic CO_2 store. In cases where unexpected leakage occurs, contractual permanence—using legal or financial mechanisms to guarantee remediation and relying on long-term human institutions—could enable the purchase of additional offsets to maintain net-zero emissions.[33]

Future work could incorporate additional reversal risks, improve understanding of climate change impacts on reversal risk, and expand the scope of CO_2 storage options considered. Choices on the location and long-term risk management strategies for biological offsets remain key uncertainties regarding their efficacy as multi-century or pseudo-permanent CO_2 stores. Additionally, estimates could be made of how much CO_2 storage is available compared with how much additional CO_2 storage is needed to stabilize long-term global temperatures. The analysis could also be extended to help distinguish between achieving true net-negative emissions and adjusting offsets for potential future releases.

METHODS

Further details regarding the methods can be found in the supplemental methods.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Conor Hickey ceh212@cam.ac.uk.

Materials availability

This study did not generate new unique reagents.

Data and code availability

All original code has been deposited at Zenodo and is publicly available at https://doi.org/10.5281/zenodo.17095568 as of the date of publication. To generate graphs on net cumulative leakage run “Storage_Profiles_Model_-July_2025.R.” To generate graphs on CO_2 concentrations and temperature impacts run “Fair climate model.ipynb.”

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AUTHOR CONTRIBUTIONS

C.H. conceived the study, conducted the analysis and risk modeling, and wrote the initial draft. S.J. led the climate modeling in FaIR and edited subsequent drafts. M.A. supervised the study.

DECLARATION OF INTERESTS

M.A. is the chair of the advisory board of Puro.earth.

SUPPLEMENTAL INFORMATION

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