

Accounting for short-term durability in carbon offsetting

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Abstract

Durability, the length of time carbon dioxide is stored before potential re-release to the atmosphere, is a critical yet underdeveloped dimension of carbon offset quality. While the voluntary carbon market trades both short-term and long-term carbon storage as fungible “one tonne” credits, the climate implications of these two classes of removal differ fundamentally. In this commentary, we examine the conceptual and practical challenges of accounting for short-term durability in carbon offsetting. We distinguish between two strategies for reconciling temporary storage with robust neutralization claims: horizontal stacking, in which credits are sequentially renewed as they expire, and vertical stacking, in which multiple short-term credits are purchased upfront to approximate the climate benefit of permanent storage. We evaluate the assumptions, trade-offs, and market constraints associated with each approach and argue that transparent, science-grounded frameworks for durability accounting are essential to the integrity of corporate net-zero claims. We conclude by recommending portfolio-based approaches that pair near-term, high-quality temporary removals with investments in durable engineered storage.

Keywords: carbon offsets; durability; permanence; temporary carbon storage; net zero; carbon dioxide removal; voluntary carbon market; ton-year accounting

1. Introduction

Consider a device that captures CO₂ from ambient air and stores it in sealed containers. One container holds the captured CO₂ for exactly 20 years before releasing it; another, constructed from an innovative material, retains the gas for millennia. How should we evaluate the relative climate benefit of these two storage durations? And what offset claims should attach to each?

Although stylized, this thought experiment highlights one of the most consequential and unresolved complexities in carbon offsetting: durability. The field has not yet converged on frameworks for comparing the climate benefit of one tonne of CO₂ stored in soil for 20 years with one tonne permanently mineralized in geological formations. In today's voluntary carbon market, both are sold as "one tonne of carbon credit," and the burden of evaluating their differential efficacy falls largely on the buyer.

This commentary addresses two foundational questions. First, what is the role of carbon storage that persists for only a decade or two relative to storage that lasts for thousands of years? Second, how can short-term storage be credibly integrated into robust offsetting claims?

2. Defining Durability

Durability in the context of carbon offsets can refer to either the *planned duration of carbon storage* or the *risk of reversal* before that planned duration is reached. This commentary focuses on the former, which is also frequently referred to in the literature as "permanence" (Herzog et al., 2003; Marland et al., 2001).

We prefer the term "durability" because it is less absolute than "permanence" and better acknowledges the temporal variability inherent to most forms of carbon storage. Even geological storage, while orders of magnitude more durable than biological sequestration, is not infinite in duration (Alcalde et al., 2018). Adopting "durability" as a graded concept, rather than treating permanence as a binary attribute, enables more nuanced evaluation of offset quality across a spectrum of storage timescales.

3. The Function of Carbon Offsets and the Neutralization Standard

There is no clear consensus on the precise function a carbon offset should serve. In the most rigorous conceptualization, a carbon removal offset represents one tonne of CO₂ removed from the atmosphere that cancels out one tonne of emitted CO₂. One tonne enters the atmosphere and one tonne is removed permanently, so that the net effect on the climate system is zero, functionally equivalent to the emission never having occurred. The Science Based Targets initiative (SBTi) refers to this as “neutralization” of emitted carbon (SBTi, 2021).

The challenge is straightforward: for CO₂ emissions to be fully neutralized, the corresponding carbon must be stored permanently. Any release of stored carbon, whether after 20 years, 100 years, or 1,000 years, causes a net increase in atmospheric CO₂, terminating the interim efficacy of the offset. Fuss et al. (2024) recently modeled this dynamic, demonstrating that CDR with storage periods of less than 1,000 years is insufficient to neutralize remaining fossil CO₂ emissions under a net-zero framework. Engineered carbon removal solutions, such as mineralization or direct air carbon capture and storage (DACCS), can store CO₂ in geological reservoirs for thousands of years (National Academies of Sciences, Engineering, and Medicine, 2019). However, the current supply of such permanent storage is limited to thousands, not millions, of tonnes CO₂ removed annually, and costs frequently exceed \$100 per tonne, far above the price of other carbon credits [cite CDR.fyi].

3.1. Temporary Storage as Delayed Emissions

As of the early 2020s, the vast majority of carbon removal credits sold in the voluntary carbon market guarantee storage for only decades to a century. This is functionally equivalent to delaying emissions rather than neutralizing them (Levasseur et al., 2012; Matthews et al., 2023). Temporary carbon storage does, however, provide real value. It can expand the pool of available carbon removal by enabling short-term contracts that lower barriers to entry for landowners. It can delay climate impacts, reduce peak warming, help avoid climate tipping points, buy time for technological development, and generate co-benefits such as ecosystem services (Marshall and Kelly, 2010; Zickfeld et al., 2022). Ecosystem services, including biodiversity conservation, clean water provision, and nutrient cycling, deserve recognition in their own right, not merely as ancillary benefits of carbon credits.

Nevertheless, these attributes are not durable carbon removal *per se*. Moreover, attributing economic value to these co-benefits within the carbon market is complex and inherently uncertain. As the number of corporate net-zero commitments accelerates, one of the greatest risks of short-term solutions is that they may be conflated with permanent neutralization, thereby providing justification for continued emissions (Carton et al., 2021; Bednar et al., 2021). It is essential that pathways to meeting climate goals be both transparent and effective.

3.2. Scope and Assumptions

This commentary discusses durability in the context of *carbon removal offsets*, which is our primary analytical focus. Avoided and reduced emissions offsets involve distinct durability considerations that lie beyond the scope of this analysis. We also assume for expositional simplicity that carbon offsets last exactly as long as they are claimed to. In practice, the risk of premature reversal (e.g., via wildfire or reservoir leakage) and the possibility of carbon storage beyond an offset's official term (e.g., in long-lived wood products) are important factors in durability assessments that warrant separate treatment.

In particular, the realized durability of nature-based carbon storage is often poorly captured by the crediting period assigned to a given offset. Empirical evidence suggests that forest carbon may persist well beyond nominal credit terms under favorable conditions, but may also be lost far sooner due to disturbance, land-use change, or climate feedbacks (Anderegg et al., 2020; Pugh et al., 2019). The relationship between credited duration and actual storage duration is thus uncertain in both directions. A full treatment of this uncertainty is beyond the scope of this commentary, but it underscores the inadequacy of treating crediting periods as reliable proxies for realized durability.

4. Accounting for Durability: Vertical and Horizontal Stacking

If carbon removal offsets claim to neutralize emissions, are there strategies by which temporary storage can contribute to this objective? Two broad approaches have been investigated in the scientific literature, which we synthesize as follows (see Figure 1 for a schematic comparison):

Horizontal stacking involves sequentially purchasing replacement offsets as prior credits expire, creating a continuous sequence of one tonne stored over time. Firms seeking to neutralize their emissions horizontally stack credits to maintain uninterrupted carbon storage.

Vertical stacking involves purchasing multiple short-term credits upfront to offset one tonne of CO₂ emitted today. Firms can fully or partially compensate for the lifetime climate impacts of present emissions by overbuying short-term credits, i.e., by vertically stacking.

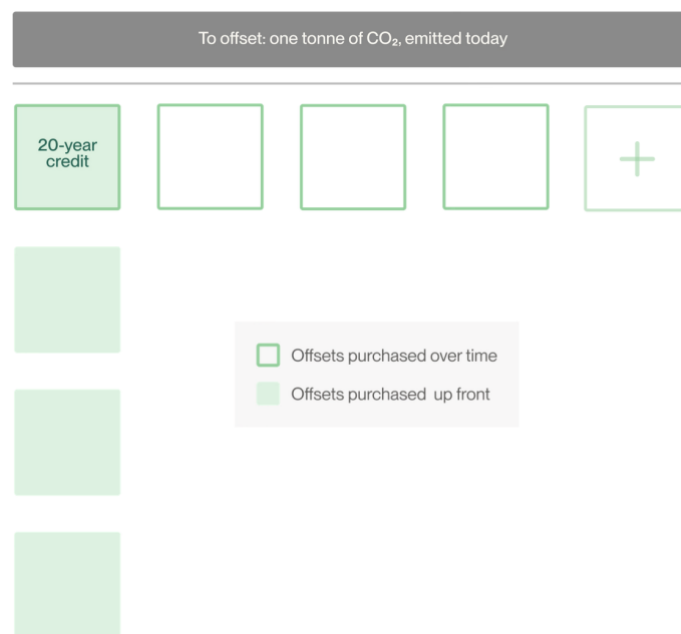


Figure 1. Schematic comparison of horizontal and vertical stacking strategies for managing short-term carbon offset durability. In horizontal stacking, sequential credit purchases maintain continuous storage over time. In vertical stacking, multiple short-term credits are purchased upfront to approximate the cumulative climate benefit of permanent storage.

4.1. Horizontal Stacking

Horizontal stacking has a certain operational simplicity: a 20-year credit purchased in 2021 must be replaced in 2041. That replacement could represent permanent geological storage, or another 20-year credit, in which case the renewal cycle continues (Herzog et al., 2003; see also CarbonPlan’s Permanence Calculator). In this framing, each short-term purchase functions as an offset lease or rental: the credit provides a climate service that eventually must be renewed. If it is not, emissions are effectively delayed but not neutralized.

The primary challenge with horizontal stacking is institutional continuity. If a purchasing firm goes bankrupt, its historical emissions persist long after there is an entity responsible for renewing offset commitments. Horizontal stacking requires consistent stewardship over long periods, which is difficult to guarantee in practice. Bednar et al. (2021) have proposed “carbon removal obligations” as one institutional mechanism to address this temporal responsibility gap, though such instruments remain largely theoretical.

One promising variant is a *bridge approach*, in which *ex-ante* engineered storage credits are purchased alongside *ex-post* short-term forestry credits to span a gap in permanent storage availability. For instance, if geologic storage capacity is expected to come online within a defined period, near-term forestry credits can provide interim coverage. This approach can achieve continuous neutralization provided the engineered storage is ultimately delivered as contracted. While not inexpensive, a bridge strategy enables full neutralization while simultaneously supporting both nature-based projects and the scaling of engineered carbon removal.

4.2. Vertical Stacking

Vertical stacking is conceptually more complex. Under this approach, a firm purchases *multiple* 20-year credits in the current year to offset one tonne of emitted CO₂ in perpetuity. The result is disproportionate climate benefits in the near term, followed by a spike in net emissions when the stored carbon is released at the end of the storage period (Figure 2). Vertical stacking thus produces oversized near-term benefits at the cost of deferred climate impacts.

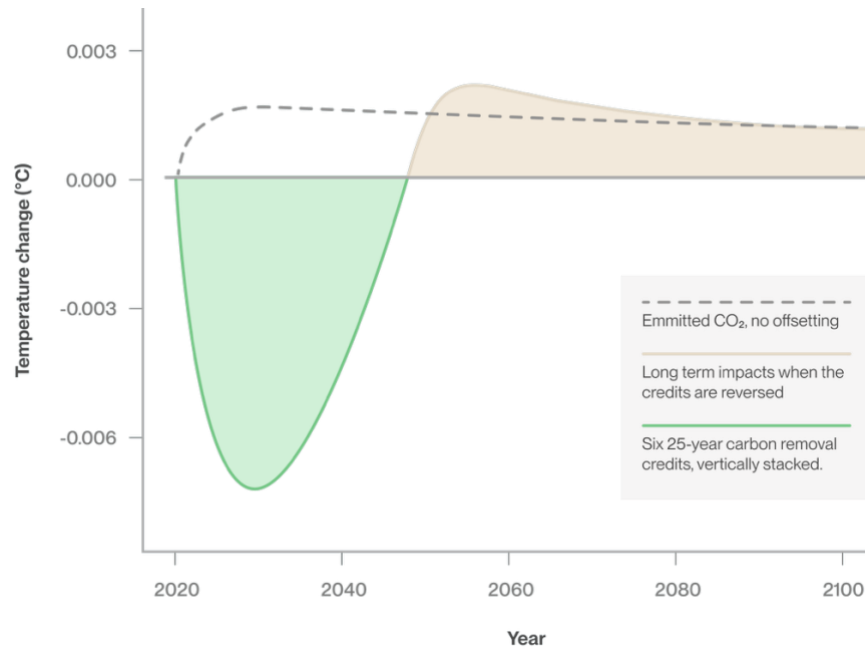


Figure 2. Illustrative example of the temperature impacts of a vertical stacking approach. Temperature change (°C) associated with vertical stacking of six 25-year carbon removal credits against one tonne of CO₂ emitted, modeled using the Finite Amplitude Impulse Response (FaIR) climate model. The dashed line shows the warming trajectory of the emitted CO₂ in the absence of offsetting. The green shaded area represents the near-term cooling benefit of the vertically stacked credits during their 25-year storage period. Upon reversal of the stored carbon (circa 2045), the net temperature effect turns positive (beige shaded area), reflecting residual warming that exceeds the no-offsetting baseline before converging toward it over the remainder of the century.

A central challenge is determining the appropriate height of the stack, that is, how many short-term credits must be purchased to approximate the climate benefit of one permanent credit.

Several equivalence frameworks have been proposed in recent years (Groom and Venmans, 2023; Parisa et al., 2022; Chay et al., 2022; Cullenward et al., 2022; Balmford et al., 2023).

These approaches share certain fundamental characteristics.

First, they all require models and assumptions about the climate system that introduce uncertainty. These frameworks are built on representations of how emitted CO₂ behaves in the atmosphere and can produce substantially different equivalence values depending on the assumptions employed. Some incorporate economic considerations through discount rates or by translating CO₂ emissions into climate-related economic damages (Nordhaus, 2017; Howard and Sterner, 2017). Ultimately, these assumptions force decision-makers to prioritize among different types of climate impacts: warming, economic damages, tipping points, or intergenerational

equity. Misspecified assumptions could direct resources toward actions that generate net harm over longer time horizons.

Second, each equivalence framework calculates the fractional value of short-term carbon storage relative to a longer reference time horizon (e.g., 1,000 years). For example, a model might estimate that 50 years of storage achieves 25% of the climate benefit of 1,000-year storage. This implicitly generates a vertical stacking ratio: if one 50-year credit is worth 0.25 of a permanent credit, purchasing four today could approximate equivalence. However, purchasing four credits may also be more expensive than a single permanent credit, undermining the cost-effectiveness rationale. Matthews et al. (2023) have recently argued that tonne-year accounting can track the climate benefit of temporary storage but should not be used to establish a strict equivalence with permanent storage, cautioning against overextending the framework.

An additional complication is normative: when is full neutralization required, and when are alternative approaches, such as vertical stacking, acceptable? These questions do not have straightforward answers. Vertical stacking forces decision-makers to weigh near-term climate benefits against deferred climate impacts, while simultaneously considering whether temporary storage contributes to avoiding climate tipping points or purchases time for decarbonization (Carton et al., 2021).

Finally, and critically, high-quality carbon removals, even temporary ones, are in short supply. Vertical stacking requires overbuying upfront. If existing supply cannot meet baseline demand without overbuying, the additional credits required for vertical stacking may simply be unavailable.

5. Looking Ahead: Scaling Durability and Quality

Direct emissions reductions should be the first priority of any organization's carbon management plan. Beyond direct abatement, however, removing carbon from the atmosphere in ways that give neutrality claims integrity, which necessarily requires accounting for durability, is essential.

Temporary carbon storage solutions play an important role alongside permanent solutions, but that role remains poorly articulated in current market frameworks. Ideally, carbon offsetting will completely neutralize a tonne of emitted carbon through removal into perpetuity. This is the least

ambiguous interpretation of “net zero.” But in today’s market, there is insufficient supply of permanent storage to meet even a fraction of demand. Similarly, the supply of high-quality short-term removal credits is too limited to support overbuying at the scale vertical stacking would require.

This supply-side constraint underscores the importance of a portfolio approach: scaling more permanent CO₂ removal systems (e.g., direct air capture with geological storage, carbon mineralization) alongside high-quality short-term carbon removal. Microsoft (2021) and other leading corporate buyers have adopted this portfolio strategy, treating near-term biological removals and long-term engineered removals as complements rather than substitutes. Zickfeld et al. (2022) provide further theoretical support, demonstrating that temporary nature-based storage can reduce peak warming, but only when complemented by ambitious fossil fuel emissions reductions.

Both horizontal and vertical stacking approaches warrant continued development, with particular attention to when each is appropriate and how each can be operationalized at scale. The aim should be to help carbon offset buyers construct portfolios that are scientifically rigorous, practically implementable, and flexible enough to adapt as understanding of these complex issues advances.

6. Conclusion

Durability is not a binary attribute of carbon offsets, but a graded characteristic that fundamentally shapes the climate efficacy of offset claims. The current practice of treating all carbon credits as fungible one-tonne units obscures critical differences in the temporal profile of carbon storage. Horizontal stacking offers a conceptually clear path to continuous neutralization but requires institutional mechanisms for long-term stewardship. Vertical stacking can approximate permanent storage benefits through upfront overbuying but depends on contested equivalence frameworks and faces binding supply constraints. Neither approach alone resolves the tension between the demand for immediate, affordable carbon offsets and the imperative for durable climate outcomes. We argue that portfolio-based strategies, combining near-term high-quality temporary removals with planned procurement of permanent engineered storage, represent the most defensible path forward for organizations seeking to make credible net-zero

claims. As the voluntary carbon market matures, robust durability accounting must become a non-negotiable element of offset quality assessment.

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