BUFFER POOLS & BEYOND

UNIFYING TERMS AND APPROACHES FOR DURABILITY STRATEGIES IN CARBON MARKETS

SHIFT CM

The Nature Conservancy Yale

Savannah D. Gupton, Program Manager & Researcher, Yale Applied Science Synthesis Program, Yale Center for Natural Carbon Capture & Yale School of the Environment, Yale University

Sara Kuebbing, Director of Research, Yale Applied Science Synthesis Program and Research Scientist, Yale Center for Natural Carbon Capture & Yale School of the Environment, Yale University

Ingrid Thyr, Postgraduate Researcher, Yale Applied Science Synthesis Program, Yale Center for Natural Carbon Capture & Yale School of the Environment, Yale University

Michelle Kirchner, Research Project Manager, Yale Applied Science Synthesis Program, Yale Center for Natural Carbon Capture & Yale School of the Environment, Yale University

Racheal Notto, Head of Carbon Markets, Kita

Lynn Riley, Lead Scientist, American Forest Foundation

William Anderegg, Professor, School of Biological Sciences and Leadership Team, Wilkes Center for Climate Science and Policy, University of Utah

Susan C. Cook-Patton, Lead Reforestation Scientist, The Nature Conservancy

Nathan Truitt, Executive Vice President, Climate Funding, American Forest Foundation

Alexander Dhond, PhD Student, Department of Biology, University of Oxford

Noel P. Gurwick, Research Scientist, University of Maryland

ACKNOWLEDGEMENTS

Please cite this report as: Gupton, S.D., Kuebbing, S., Thyr, I., Kirchner, M., Notto, R., Riley, L., Anderegg, W., Cook-Patton, S.C., Truitt, N., Dhond, A., Gurwick, N.P., and the Beyond Buffer Pools Working Group (2026) Buffer Pools & Beyond: Unifying Terms and Approaches for Durability Strategies in Carbon Markets. Science for High Integrity Frameworks to Transform Carbon Markets (SHIFT-CM) White Paper.

This paper benefited from contributions of many experts.

Initial discussions identifying the need for this white paper occurred during a December 2024 SHIFT-CM workshop co-hosted by the Yale Applied Science Synthesis Program and The Nature Conservancy. The workshop was held at The Forest School at the Yale School of the Environment and supported by the Yale Center for Natural Carbon Capture. The workshop brought together participants from multiple sectors involved in practice, policy and research around carbon markets, carbon accounting, and forest ecology. At the workshop, participants identified the need to synthesize alternative institutional structures to manage reversal risk liability and formed the "Buffer Pools and Beyond" working group, which has been meeting regularly since the initial workshop.

The Yale Applied Science Synthesis Program (YASSP) is a joint initiative of the Yale Center for Natural Carbon Capture and The Forest School at the Yale School of the Environment, whose mission is to generate science to support decision making. YASSP produces quantitative, reputable and open scientific syntheses that guide and inform direct actions around land stewardship. One aim of the Program is to be a neutral organizing space for socializing and advancing ideas that advance biodiversity, climate and human goals related to ecosystem management. YASSP has no commercial interests in carbon markets. The following YASSP staff participated in SHIFT-CM efforts to develop this paper: Sara Kuebbing, Director of Research, SHIFT-CM Hub Co-Lead, and Working Group Co-Lead; Savannah Gupton, Program Manager & Researcher, Working Group Lead; Michelle Kirchner, Research Manager and Working Group participant; Ingrid Thyr, Postgraduate Associate and Working Group participant.

The Nature Conservancy (TNC) is a global environmental nonprofit working to create a world where people and nature can thrive. Founded in the US through grassroots action in 1951, TNC has grown to become one of the most effective and wide-reaching environmental organizations in the world. Using a science-based collaborative approach, TNC works in over 80 countries to protect habitats, tackle climate change, and secure freshwater. TNC holds some commercial interests in carbon markets as a carbon project developer, and revenue is used to advance conservation goals. TNC has established internal quality requirements that, alongside leading third-party certification standards, inform their project development process. In 2021, TNC conducted a thorough review of their carbon portfolio and adjusted crediting to meet these new standards. The following current and former TNC staff participated in SHIFT-CM efforts to develop this paper: Peter Ellis, Global Director of Natural Climate Solutions Science and SHIFT-CM Hub Co-Lead; Kim Myers, Senior Carbon Markets Associate and SHIFT-CM Hub Co-Lead; Max Bernal Temores, Carbon Market Researcher and SHIFT-CM Hub Co-Lead.

The authors acknowledge the following working group members for their expert contributions to this work: Elizabeth Guinessey, Verra; Carl Kish, Beyond Alliance; Joe Fargione, The Nature Conservancy; Bariki Lelya, Open University of Tanzania; Candace Vinke, Verra; Luke Pritchard, Beyond Alliance; and Nicole Gotthard, Yale University.

The authors also acknowledge the following external reviewers who provided helpful comments and contributions to an early draft of this white paper: Teresa Lang, Senior Director, Policy, Anew Climate; Caroline Ott, Founder & Principal, LongRun Climate; Maximiliano Bernal Temores, Carbon Market Researcher, The Nature Conservancy and SHIFT-CM Hub Co-Lead; Peter Ellis, SHIFT-CM hub lead and The Nature Conservancy; and Dr. Jennifer Jenkins, Chief Science Officer, Rubicon Carbon.

Design: Puntoaparte.com.co. Cover image: Thommy TFH, Shutterstock.com

CONTENTS

EXECUTIVE SUMMARY

Natural climate solutions are an essential component of the world's climate mitigation portfolio. To constrain global temperature below catastrophic warming of 2°C, we must immediately reduce land-based emissions and enhance ecosystem carbon storage. Decades of experience protecting, managing, and restoring ecosystems provide many examples of successes and lessons learned as natural climate solutions are implemented at scale. As we deploy nature-based carbon projects for carbon crediting, it is critical to ensure carbon storage meets desired durability thresholds by remaining out of the atmosphere long enough to fulfill specific policies or climate mitigation goals.

To date, carbon crediting standards typically address durability during the contractual crediting period, or guaranteed durability period, by withholding a percentage of carbon credits from a project in a buffer pool. When disturbances like wildfire or land conversion lead to a net loss of carbon from the project into the atmosphere, they "reverse" the emission reductions or removals. When reversals occur during a carbon credit's guaranteed durability period, a sufficiently-stocked buffer pool can replace the reversed credit and effectively continue the carbon storage.

Although buffer pools will likely continue to play a key role in addressing reversals, two lines of evidence suggest a need for additional approaches to support the durability of nature-based carbon credits. First, projections of increasing forest carbon loss due to disturbance reinforce longstanding concerns that buffer pools may not be able to fully compensate for growing frequency and severity of reversals. Second, many market actors seek nature-based credits that deliver climate mitigation beyond their guaranteed durability periods. These actors may therefore pursue approaches that either extend the time carbon remains out of the atmosphere (or the realized durability of a credit) or compensate for carbon losses after the end of a credit's guaranteed durability period.

Image: Daily_creativity, Shutterstock.com

This paper synthesizes for the first time a suite of approaches that could complement buffer pools to increase the durability of nature-based carbon credits. These approaches range from well-established practices to emerging ideas, each with its own advantages and limitations. We also propose and define terminology that offers the nuance needed to characterize the features of each approach clearly and to compare them. We demonstrate how shifting definitions from strict binaries (permanent or not) to a continuous measure of durability better reflects reality and creates opportunities to make long-term plans that can flexibly deploy climate solutions today and into the future. By presenting new terminology, organizing approaches in a typology, and evaluating approaches according to a set of consistent criteria, this paper assists market actors in discussing, comparing, and identifying appropriate approaches for their business and policy contexts. Our taxonomy and definitions provide common lexicon and categorization of approaches that market actors may now debate, test, and analyze for feasibility and reliability in climate mitigation actions.

We identified seven approaches that we organize into three general strategies: risk-transfer, purchasing, and accounting. These are not mutually exclusive, and several can be deployed together.

Risk-transfer strategies shift non-permanence risk from one market actor to another, typically aggregating the risk from multiple market actors and thus diluting the risk associated with any particular geography, project, or location. These strategies include buffer pools, carbon trust funds, and insurance.

Purchasing strategies focus on strategically investing in credits to ensure credits meet durability thresholds and include vertical and horizontal stacking.

Accounting strategies adjust carbon storage estimates and include risk-weighted and time-weighted accounting.

A key theme that emerged from this effort is that all approaches will benefit from improved data quality and transparency. However, our synthesis suggests there are many emerging ideas that could complement buffer pools to enhance the durability and diversify the risk management of nature-based carbon credits. Each solution brings a unique set of benefits and limitations, and combinations of approaches may more effectively manage risk than any single approach.

SCOPE & AUTHORSHIP TEAM

This paper was authored by a group of researchers based at universities and environmental non-profits along with carbon market professionals. The authors were supported by the Science for High-Integrity Frameworks to Transform Carbon Markets (SHIFT-CM), a multi-stakeholder initiative co-led by the Yale Applied Science Synthesis Program and The Nature Conservancy. This initiative is focused on improving the scientific foundation of ecosystem-based carbon crediting.

The IPCC has consistently emphasized that investing in ecosystem carbon storage is essential to meeting global temperature goals. However, there are significant risks to nature-based carbon storage that must be identified and addressed to support natural climate solutions as a climate mitigation tool, particularly when used within carbon markets as offsets to fossil-based emissions. To that end, the members of this working group gathered to identify, discuss, and outline potential approaches and solutions to enhancing the durability of nature-based carbon credits. The authorship team believes that natural climate solutions should not be sidelined in carbon markets due to potential risks of carbon loss, and buffer pools—the most commonly employed approach in markets to date—have a longstanding history of implementation and use that addresses many, but not all, concerns about the non-permanence risk of nature-based carbon credits in the market. Depending on specific use cases and market actor climate goals, different suites of approaches may support the climate mitigation potential of natural climate solutions. We believe it is worthwhile to discuss, study, pilot, and implement at scale various approaches to reduce and address natural climate solutions' non-permanence risks. Ultimately, a diversity of options will make it more possible to robustly implement natural climate solutions.

The goals and scope of this paper are to present: (1) a common terminology to discuss carbon storage durability; (2) a taxonomy of all the approaches that have been discussed to date in carbon markets; and (3) a qualitative overview of how each approach is supposed to work. With this foundation, we can then begin to answer questions about which combination of approaches are most useful in which contexts and the best ways to implement and scale approaches in today's markets.

We caution that any of these approaches can be applied judiciously or poorly in practice. We also note that these approaches will be more successful if the project developer is engaging in all possible management activities to reduce risks on the landscape. With the exception of buffer pools, most of these approaches have had limited to no adoption in markets, meaning that more data and analyses would benefit market actors implementing newer approaches. We hope this paper spurs further analysis to identify the most promising combinations of approaches for given use cases and market actors, which will likely lead to more judicious implementation. If implemented poorly, these practices could have no, or even negative, climate impacts. Therefore, we highlight challenges and cautions related to implementing these approaches.

We focus predominantly on natural climate solution activities in carbon markets issuing project-based carbon credits. While we do not delve into other climate mitigation activities, non-market funding structures, or jurisdictional crediting in this paper, we do believe that some of these approaches are highly adaptable and there are lessons learned from this paper that could be applied to these areas.

INTRODUCTION

Climate change mitigation efforts seek to avoid climate warming by rapidly decreasing greenhouse gas emissions and removing excess carbon dioxide from the **atmosphere**. **Natural climate solutions** are **mitigation activities** that protect, manage, and restore natural ecosystems to reduce greenhouse gas emissions and store carbon (1). Ecosystem carbon cycling is dynamic: ecosystems can emit carbon to the atmosphere when they are disturbed and regain carbon as they recover from disturbances.

Reducing land-based emissions and enhancing ecosystem carbon storage is essential to achieving near- and long-term climate change mitigation goals (2,3). However, ecosystem disturbances such as land conversion, wildfires, and extreme weather that result in significant carbon loss have raised concerns that nature-based carbon storage may be too temporary or impermanent to be reliably used for **climate change mitigation claims** with long **durability thresholds**, like offsetting fossil-fuel based emissions. These concerns have decreased funding to, and implementation of, nature-based **carbon projects**.

Long-term carbon storage is critical to reduce the long-term impacts of climate change and achieve climate stabilization (2,4). As a result, **permanence** has been a central criterion of climate change mitigation solutions and a dominant feature of carbon markets and net-zero goals. Carbon markets have increasingly focused on classifying climate change mitigation solutions as either “permanent” or “impermanent”, typically using a 1,000+ year time horizon to parse the two (5). However, this strict dichotomy masks important nuances in estimating how long and across what spatial scales nature-based climate solutions can be expected to store carbon. A high risk of carbon loss for some crediting projects does not mean that all ecosystem-based solutions—especially aggregated across large spatial scales—offer only “short-term” storage. Some forests and soils have consistently and reliably stored carbon for thousands of years (6,7,8).

Crucially, the level of permanence required is inherently tied to the climate change mitigation claim supported by the **carbon credit**. There are a few potential climate mitigation claims: A compensation claim that asserts physical climate equivalence—such as neutralizing the long-term temperature impacts of fossil fuel carbon dioxide emissions—requires a much longer durability threshold than a claim to reduce peak global temperatures or to slow the rate of near-term temperature increase. **Buyers** may also use nature-based carbon credits to meet contribution claims that communicate a commitment to climate solutions without necessarily tying them to specific emission or temperature goals. Climate scientists and policy makers are just beginning to define and articulate how different durations of carbon storage can achieve different climate mitigation goals (9,10,11).

While ecosystems can store carbon for periods ranging from years to millennia (12), unpredictability in the timing or severity of disturbances requires that nature-based carbon credits are designed and issued with provisions that enable compensation for disturbance-driven carbon losses that could occur in the future. Traditionally, **project developers** and **standards bodies** have focused on two actions:

- **Addressing permanence vulnerabilities at a project site:** **Permanence vulnerabilities** are characteristics such as ecology, location, governance stability, social cohesion, or management capacity that predispose ecosystem carbon to be emitted back to the atmosphere earlier than desired for a given policy goal, use case, or claim (a **reversal**). Carbon crediting projects have a range of characteristics that can increase or decrease the likelihood a project or credit will experience a reversal; this likelihood is the project's **non-permanence risk**. Various tools and approaches have been developed within the carbon market to reduce non-permanence risk. These approaches may incentivize siting projects in locations with reduced disturbance risks and management activities that reduce the probability of carbon loss, such as thinning trees to reduce fire risk or enhancing the connectivity of communal grazing areas.
- **Compensating for reversals when they occur:** Because ecosystem **carbon sinks** are vulnerable to disturbances, and that vulnerability is increasing globally due to land use change, climate change, and their interactions, there will always be non-permanence risk for an ecosystem- or nature-based carbon project. Therefore, to keep carbon storage claims intact, crediting methodologies have created mechanisms to compensate for reversals, where reversals may be designated as either **avoidable (intentional)** or **unavoidable (unintentional)** (13). In current market methodologies, the primary approach to compensate for unavoidable reversals is the use of **credit buffer pools**. Under this approach, a portion of a project's carbon credits is reserved to replace credits that may be reversed in the future.

There are growing concerns that current approaches to reduce non-permanence risk and compensate for reversals may not be sufficient (14,15). Carbon market actors are responding to these concerns by seeking improved risk data and by innovating and testing a variety of approaches that can complement buffer pools to enhance overall credit **durability**. In this white paper, we review and synthesize current and developing approaches to support the durability of ecosystem-based carbon credits. We begin by describing the current permanence and durability discourse and providing more context on reversals.

Image: Artush, Shutterstock.com

PERMANENCE AND DURABILITY

The concepts and terms "permanence" and "durability" are ubiquitous in carbon crediting. Recently, the technical differences and similarities between the two concepts have inspired debate and, potentially, confusion. Some carbon market actors use the terms synonymously while others draw distinctions between them. To enable measurable outcomes, policy goals, and international cooperation, carbon markets require conceptual and linguistic alignment.

Within carbon markets, permanence describes the length of time that a project intends to keep greenhouse gases out of the atmosphere as a result of a mitigation activity with enough certainty to support a claimed climate benefit. Some mitigation activities—particularly those that avoid emitting greenhouse gases altogether—are infinitely permanent. Two examples are when heating, electricity supply, or transportation shifts from a high- to a low- or no-emissions technology or when lower rates of nitrogen fertilizer use reduce nitrous oxide emissions. Many other mitigation activities, including many natural climate solutions, ocean fertilization, and CO_2 injection into sandstone formations, are subject to various degrees of disturbance and potential release of greenhouse gases back to the atmosphere (16). Long-term climate mitigation requires fossil fuel emissions to be kept out of the atmosphere for 1000+ years, leading some to suggest that mitigation activities that store carbon for less than this threshold should be considered impermanent (17,18). Grouping these mitigation activities into a single "impermanent" category masks that the durability of ecosystem carbon sinks varies along a spectrum from more to less durable.

Replacing binary "permanent" or "impermanent" labels with a continuous concept of durability more accurately reflects the dynamic nature of ecosystem carbon storage and allows for nuances obscured by the concept of permanence as widely applied within carbon markets. Crucially, applying durability does not relax rules and guidelines about how long carbon storage should last. Instead, the concept of durability for emissions and climate mitigation activity accounting provides a more precise and deeper understanding of non-permanence risk and related climate mitigation claims. This added precision, in turn, strengthens integrity and increases trust and transparency within the carbon market.

To provide clarity for discussing approaches to mitigate non-permanence risk and compensate for reversals, we define the following terms:

Durability: A metric for permanence that comprises two components: the timeframe credited **carbon dioxide equivalent** is held out of the atmosphere; and the likelihood the carbon dioxide equivalent will remain stored for this timeframe.

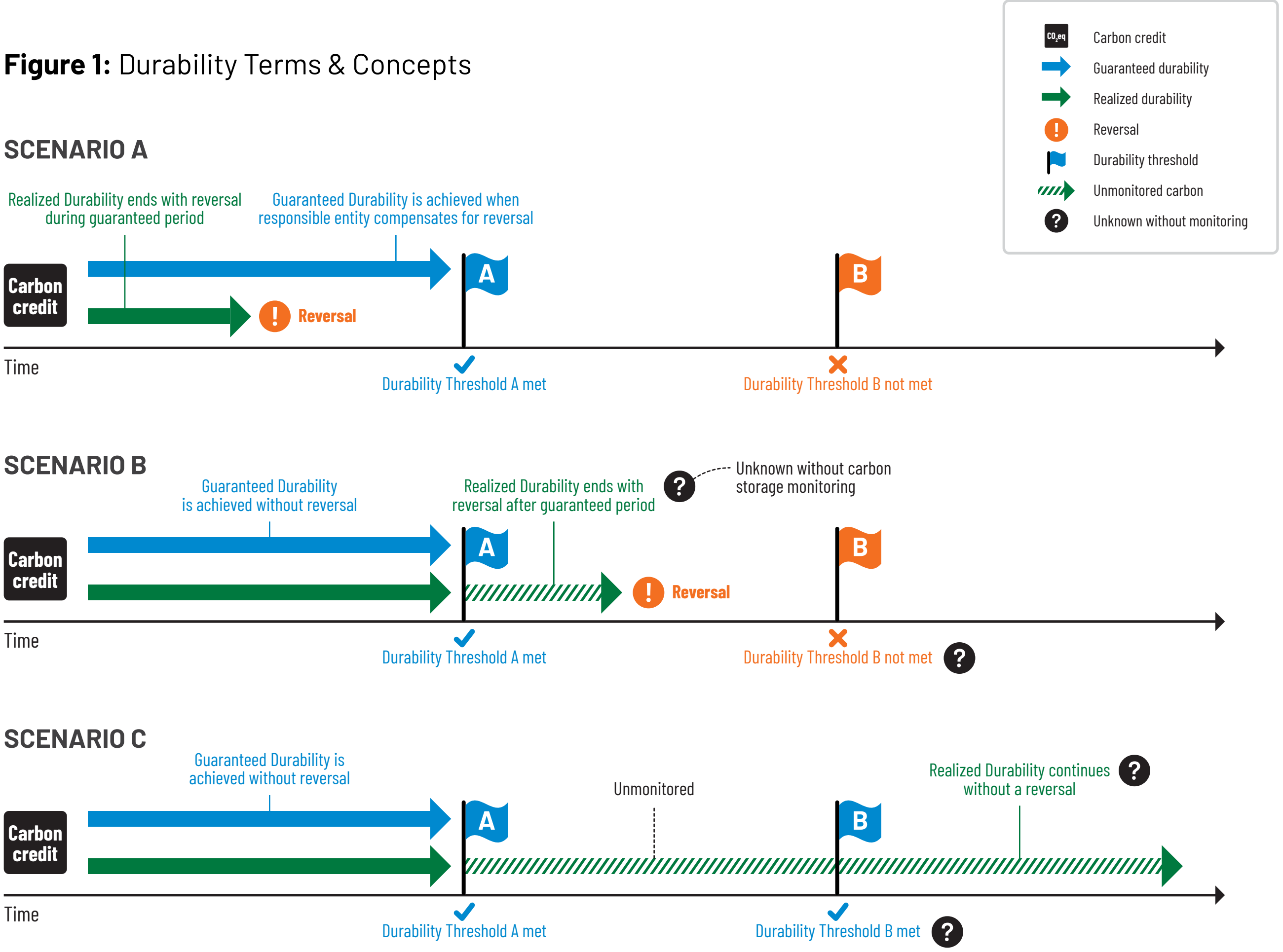
Durability Threshold: A length of time that a tonne of carbon dioxide equivalent, represented by a carbon credit, must remain out of the atmosphere to meet a particular policy goal, use case, or claim. Different policy frameworks or standards may require different durability thresholds for meeting different climate goals.

Estimated Durability: A projected estimate of the length of time a tonne of carbon dioxide equivalent will remain stored out of the atmosphere based on risk assessments of carbon loss from a given carbon sink. Estimated durability may be calculated **ex ante** at different scales–for example, a single forest stand or for a jurisdiction–and for different **carbon pools**.

Guaranteed Durability: The length of time a tonne of carbon dioxide equivalent is guaranteed to remain out of the atmosphere by an entity, often through contractual or legal means.

Realized Durability: The length of time a tonne of carbon dioxide equivalent remained out of the atmosphere. Importantly, realized durability can only be known once the carbon is emitted back to the atmosphere or **ex post** a reversal.

Figure 1: Durability Terms & Concepts



In distinguishing between these different durability terms, we highlight an important consideration in their application—the distinction between geophysical reality and what is known. Because durability thresholds are defined by policy goals and guaranteed durability is based on contract length, they are known quantities. However, realized durability is based on the geophysical reality of the land and cannot be known without continuous monitoring. In current carbon markets, carbon pools are monitored and verified during the guaranteed durability period. Thus, when a reversal occurs during this period, the realized durability of the credit is known, and the responsible entity can compensate for the reversal to meet the guaranteed durability commitment (Scenario A). Carbon pools are rarely monitored beyond the guaranteed durability period in today's markets, and for this reason, carbon monitoring is not depicted after the guaranteed durability ends in this or subsequent figures. Without this long-term monitoring, it is impossible for market actors to confirm whether or not a credit's realized durability ultimately meets a durability threshold beyond the guaranteed durability period (Durability Threshold B in Scenarios B & C).

NON-PERMANENCE RISK

All stored carbon has permanence vulnerabilities: climatic, ecological, governance, or management characteristics that predispose a carbon crediting project to experience a reversal. Examples of ecosystem-related permanence vulnerabilities include, but are not limited to, susceptibility to wildfires, droughts, temperature stress, pests and pathogens, or wind events. Risks to carbon credits may include management failures such as illegal harvesting or overharvesting that lead to the unplanned release of stored carbon. There are also institutional risks such as policy changes, methodology revisions, governance changes, and financial failure of the developer, standard body, or credit broker (19).

If a reversal occurs, stored carbon is released back into the atmosphere, and associated climate benefit claims and credits are invalid unless the loss is compensated with an equivalent amount of stored carbon. In current carbon markets, the responsibility for compensating reversals depends on when and why reversals occur. Standards bodies frequently share liability with project developers by classifying reversals into avoidable (or intentional) and unavoidable (or unintentional) reversals:

- **Unavoidable Reversals:** If events beyond the project developer's control, such as wildfires, pest outbreaks, or other natural disasters cause the reversal, the standards body assumes the liability and typically compensates for the reversal with credits from the buffer pool. If buffer pools are well-stocked, this approach is likely sufficient. However, if buffer pools are under-stocked due to increasing environmental uncertainties, then standards bodies may need to consider additional approaches to ensure they can cover future reversal liabilities.
- **Avoidable Reversals:** If the reversal is caused by factors within the project developer's control, such as poor project management or failure to maintain mitigation activities like preventing timber harvests or soil tillage, the project developer is typically responsible. They may compensate by using their stock of unsold credits or purchasing new credits. This system incentivizes project developers to mitigate non-permanence risks through careful project design and management practices. However, if they cannot fulfill their reversal compensation obligations due to financial constraints or poor project conditions, standards bodies will likely have to reassume liability. This potential situation underscores the importance of having adequately-sized buffer pools and multiple approaches to addressing non-permanence risks.

While most standards bodies use these distinctions to assign liability for reversal compensation during the guaranteed durability period, definitions of avoidable and unavoidable reversals vary across standards bodies and may evolve as policy goals change.

Furthermore, after a credit's guaranteed durability period ends, standards bodies are no longer liable for monitoring or compensating reversals, which has led market actors to explore additional approaches that complement buffer pools. Some standards bodies retire buffer pool credits to achieve an estimated durability past the guaranteed durability period. Buyers wishing to extend their climate claims beyond a credit's guaranteed durability period must assume responsibility.

They may selectively purchase credits to extend the realized durability of their claim (see Purchasing Strategies) or deploy strategies that combine carbon credits with different risk profiles and guaranteed durability periods (see Risk-Weighted Accounting and Risk-Transfer Strategies).

This paper outlines the key characteristics and functions of non-permanence risk management approaches in carbon markets. We categorize seven approaches for managing non-permanence risk into three major strategies: **risk-transfer**, **purchasing**, and **accounting**. For each approach, we assess who compensates for reversals, how climate mitigation claims are maintained, which market actors drive implementation, how the mechanism functions within carbon markets, and how its use may influence credit supply and demand. While not exhaustive, the following narratives discuss advantages and limitations of each approach to clarify options for managing non-permanence risk in the carbon market.

Figure 2: Taxonomy of Durability Strategies & Approaches

DURABILITY STRATEGIES

PURCHASING

Involves selectively purchasing carbon credits to extend the realized durability of a claim.

APPROACHES

Vertical Stacking
a market actor initially over-purchases a volume of carbon credits whose guaranteed durability sums to an amount greater than the buyer's total estimated emissions for a given time period

Horizontal Stacking
a buyer purchases new carbon credits at the end of the guaranteed durability period or if a reversal occurs to increase the realized durability of a tonne of stored carbon dioxide equivalent

RISK-TRANSFER

Reallocates non-permanence risks from one market actor to another market actor. Generally, risk transfer strategies attempt to lower financial or climate risk by pooling risk across a larger number of projects or market actors.

APPROACHES

Credit Buffer Pools
a portion of carbon credits generated from carbon projects are withheld from sale and are used to replace credits if a reversal occurs

Carbon Trust Fund
a fee is deposited into a financial trust managed by an independent market entity taking on permanence vulnerabilities

Insurance
an insurance provider is contractually obligated to supply financial or carbon credit equivalent compensation in the event of a covered loss, including a reversal

ACCOUNTING

Involves quantifying the value of a carbon credit based on a credit's estimated durability, non-permanence risk, and/or the climate impact of carbon storage.

APPROACHES

Risk-Weighted Accounting
a market actor employs approaches from financial risk management to create balanced and diversified portfolios of carbon credits or carbon projects that minimize overall risk

Time-Weighted Accounting
estimates the time-integrated climate impact of carbon storage or emission reductions over predetermined periods

RISK-TRANSFER STRATEGIES

Risk-transfer strategies shift non-permanence risk from one market actor to another market actor that assumes the liability for potential reversals and manages that risk by pooling it across a larger number of projects or market actors. As a result, these strategies rely on the stabilizing nature of a large, multi-player market. Credit buffer pools, **insurance**, and **carbon trust funds** are three risk-transfer approaches discussed in this paper.

CREDIT BUFFER POOLS

A credit buffer pool is a portion of carbon credits generated from climate mitigation projects held in reserve, most often by a standards body. This buffer pool is used to replace lost credits following a reversal that occurs during the guaranteed durability period. By allocating a portion of the credits generated by a project to the buffer pool, project developers transfer non-permanence risk to the standards body that aggregates buffer pool credits across many projects.

Buffer pools do not extend the estimated durability of a carbon credit, because they do not directly reduce the permanence vulnerabilities of the specific tonne of carbon dioxide equivalent a credit represents, such as susceptibility to wildfire or financial failure of a project developer. However, if buffer pool contribution requirements are based on how well the project proponent's management reduces permanence liabilities, buffer pools could incentivize management behaviors and project site selections that would lead to a longer estimated durability of the credit. Moreover, adequately-sized buffer pools can increase confidence in the guaranteed durability of a carbon credit by providing a mechanism to compensate for reversals, ensuring the climate mitigation claim is met via a replacement buffer credit if a reversal occurs.

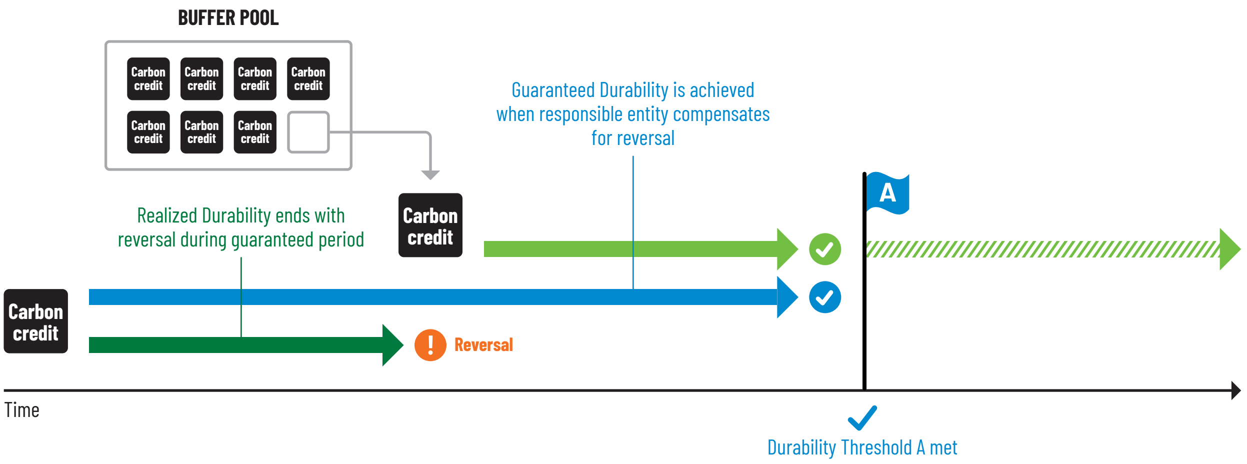
To date, buffer pools are the most commonly employed mechanism to compensate for reversals in nature-based carbon crediting protocols. Estimates suggest 10-20% of generated credits are currently reserved in buffer pools (10,20). Standards bodies vary in how they create buffer pools. Some require a fixed contribution of credits from each project, while others require a risk assessment to determine appropriate contributions based on estimated durability. Risk assessments may be updated throughout the project's lifetime to account for changes in permanence vulnerabilities. Nearly all standards bodies also set a maximum acceptable level of non-permanence risk for credited projects, providing a threshold of tolerable risk and discouraging the issuance of credits to projects with high-risk profiles.

Standards bodies are responsible for appropriately sizing buffer pools to match the total non-permanence risk across all projects. If a buffer pool is inadequately sized, it may be unable to fully compensate for reversals. Most standards bodies release buffer pool credits only for unavoidable reversals and require project developers to replace reversed credits from avoidable reversals by generating or purchasing replacement credits through existing or new projects. The success of such replacement depends on the enforceability of contracts across jurisdictions where projects are located, the ability of project developers to generate replacement credits, and the quality of the replacement credits. Standards bodies differ in how they manage buffer pools following an unavoidable reversal. Sometimes credits are cancelled directly from the pool, and sometimes project developers are required to replenish the buffer pool, similar to avoidable reversals. In both cases, the climate mitigation claim is preserved, provided the buffer pool is sufficiently large to cover the reversal. Market actors managing buffer pools may use both ex ante assessments to stock the buffer pool and ex post assessments following a reversal to ensure adequate compensation.

While standards bodies are the most common market actors to use the buffer pool approach, other market actors could also apply this mechanism. For example, the Integrity Council for the Voluntary Carbon Market's Continuous Improvement Work Program (ICVCM CIWP) Permanence Report suggests that an industry-wide buffer pool managed by a third party could serve the entire market by spreading non-permanence risk across a wider diversity of projects (14). If the industry-wide buffer pool were sufficiently large and included credits with a broad range of estimated durabilities, it could potentially reinforce the guaranteed durability of credits.

A key limitation of buffer pools is the ability to accurately estimate non-permanence risk to appropriately capitalize the buffer pool. This is further complicated by the variety of methods that standards bodies use to assess non-permanence risk of a project. Some standards bodies rely on standardized risk assessment methods, developed internally or by third parties, that apply the same assessment across all projects. While standardized risk assessments are transparent and reduce information asymmetry between project proponents and standards bodies, they are constrained by the need to generalize across diverse project types and geographies or by reliance on site-specific risk maps that require continual updating. Without any additional tools to reward risk mitigation activities, standardized risk assessments may also fail to incentivize project proponents to reduce non-permanence risk. For example, under a standardized risk assessment, a forest project proponent in a high-risk fire area who implements management that prioritizes fire risk reduction would apply the same buffer pool contribution as a project in the same region that doesn't implement the same fire risk

Figure 3: Crediting Buffer Pools



reduction management. Other standards bodies use project-specific risk assessments, where project proponents provide detailed information on a project's permanence vulnerabilities. These approaches are better suited to capturing local non-permanence risks, but they shift the information burden to project proponents, potentially increasing costs and reducing transparency across methodologies, and are not independently determined and thus might underestimate risks (21,22,23,24).

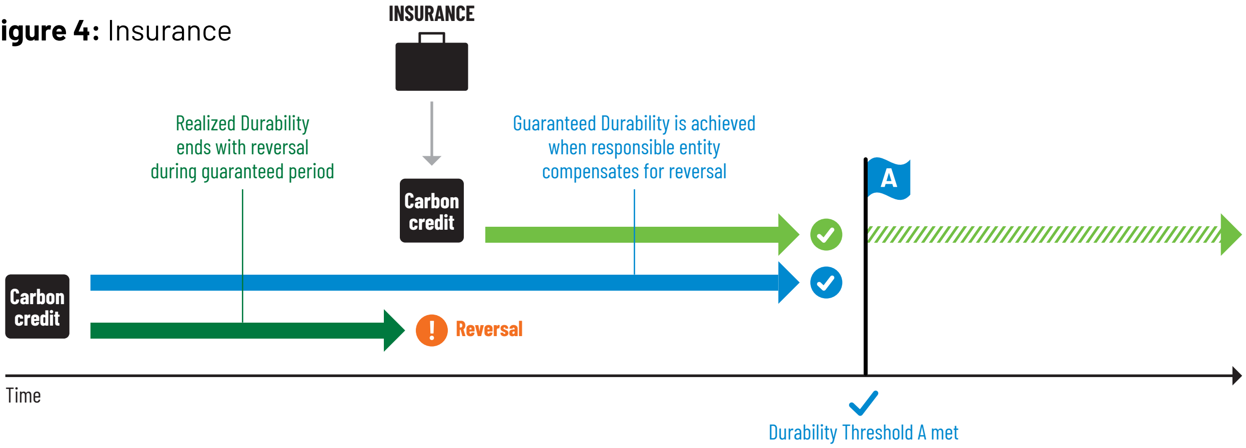
INSURANCE

Insurance is a risk-transfer approach in which a project developer, buyer, or other market actor purchases coverage from an insurance provider that is contractually obligated to provide financial compensation or an equivalent amount of carbon credits in the event of a covered loss, including a reversal. Insurance does not lower non-permanence risk associated with a carbon credit, but it does provide a clear remedy for the insured when a covered loss occurs. Insurance providers assess a credit's non-permanence risk to determine the appropriate insurance premium. Through insurance, the insured replaces uncertainty about future losses with certainty of coverage. Increased adoption of insurance may support carbon market scalability by improving risk pricing and management and by channeling additional financial resources directly to carbon projects. There are multiple insurance models relevant to managing non-permanence risk:

Private insurance is provided by insurance providers and purchased by market participants. Insurers determine which risks to cover based on profitability and diversification, as well as the coverage terms, premiums, and payouts. Insurance compensation is provided for reversals after they have occurred. There are many potential variations of reversal insurance. For example, standards bodies may purchase reversal insurance on their buffer pools, project developers may purchase reversal insurance on their carbon project, or buyers may purchase reversal insurance on a tranche of carbon credits. Project developers may purchase insurance on unavoidable reversals while standards and buyers can insure both unavoidable and avoidable reversals.

- Parametric insurance triggers payments based on predefined conditions that might signal an upcoming reversal, such as decreasing rainfall or satellite-detected forest loss, enabling rapid and clearly defined financial responses prior to reversal. If a project proponent purchases this type of insurance, they may be able to use insurance payouts to manage ecosystems to prevent a reversal from occurring.
- Public insurance is provided and operated by governments that use public resources to ensure affordability, accessibility, and adequacy of coverage, particularly for risks that are underserved or uninsurable in private markets.
- Public-private insurance involves collaboration between governments and private insurers to provide regional or national insurance programs for broad-based protections, such as against widespread deforestation.
- Catastrophe bonds are insurance-linked securities designed to cover low-probability but high-impact events such as earthquakes or cyclones. Insurers distribute payments when a predefined catastrophic event occurs and are used to finance recovery or restoration efforts.

Figure 4: Insurance



Presently, at the publication of this paper and to the authors' knowledge, the forms of carbon insurance implemented in the market are private insurance and public-private insurance (MIGA). The other forms described above are not currently implemented in carbon markets.

Because insurance can take many forms and be purchased by a variety of market actors, its impacts on non-permanence risk and credit durability can vary. Private insurance may indirectly reduce non-permanence risk by incentivizing insured project developers to mitigate permanence vulnerabilities if that would lower insurance premiums. Parametric payments may allow proponents to respond quickly to limit reversal threats. Public or public-private insurance could directly reduce non-permanence risk if governments mandate specific risk-reduction measures as part of the insurance policy. Designed to cover low-probability reversals, catastrophe bonds will likely have no impact on risk mitigation efforts. When entities other than the project developer, such as carbon credit buyers or carbon standards, are the insured, they have limited ability to directly reduce non-permanence risk as they do not directly manage the carbon project.

Most insurance mechanisms can reinforce the guaranteed durability—and thus the carbon storage claim—of carbon credits, but only if the end result of an insurance policy claim yields compensatory carbon credits. The decision to pay out a claim in cash or carbon credits is specific to the scenario the insurance is applied to and is best discerned on a claim by claim basis. Private insurance only guarantees the insured market actor is compensated, and claims may be paid out in cash or in carbon credits. When insurance policies compensate claims with cash, the guaranteed durability is only preserved if the insured uses the payment to repurchase a new carbon credit. Public or public-private insurance may more robustly protect guaranteed durability than private insurance because government backing allows for greater coverage of large-scale, systemic, or long-term risks that private insurers may be unwilling or unable to assume. Public programs could also mandate that insurance payments are used to replace any reversed credits. Catastrophe bonds can preserve guaranteed durability as long as they are comprehensive in the catastrophes they cover. For most types of insurance, there is an ex post quantification of carbon stored and carbon losses as the insurance claim is activated after a reversal occurs.

Insurance has several limitations. First, coverage only guarantees credit durability for the duration of the policy, which is typically one to five years for private insurance. If the insured does not renew or the insurer does not extend policies, which may occur when risks and premiums become too high, guaranteed durability beyond the current policy is at risk. Public or public-private insurance policies may assume longer-term risk than private policies that better align with guaranteed durability periods. Second, if the insured is the project developer, insurance is generally limited to causes of unavoidable reversals. When project developers hold both the credit and the policy, conflicts of interest may arise and may reduce incentives to prevent or mitigate avoidable reversals. As a result, insurers may limit coverage for avoidable reversals or enforce lengthy claims processes, potentially undermining guaranteed durability. Buyers and carbon standards who do not directly manage projects may obtain more comprehensive coverage for both avoidable and unavoidable reversals, since they lack such conflicts of interest. Third, insurance claims processing may be slow, limiting utility of insurance for frequent, low-impact reversals. Fourth, carbon credit price volatility—which may arise from inflation, currency fluctuations, or market valuation shifts—adds uncertainty to claims payments. Some insurers can ameliorate this limitation by offering claims in cash or replacement carbon credits. Finally, like buffer pools and other approaches, insurance relies on accurate non-permanence risk assessments. If risk is underestimated for a substantial proportion of insured projects, issues arise regarding type and size of coverage.

CARBON TRUST FUND

A carbon trust fund is a risk-transfer approach in which carbon credit purchases include a fee that gets deposited into a financial trust. Fees may be assessed at various points during the carbon credit's life cycle and paid by a variety of carbon market actors, depending on how the trust is designed. An independent market entity manages the trust and assumes non-permanence risk for a durability threshold. Carbon trust funds are modeled after financial trust arrangements, in which a trustee manages assets according to rules established by a grantor for the benefit of a beneficiary. In the carbon context, the assets being managed are the fee and the revenue from the fee, which are designated to enable actions that preserve the climate mitigation claim represented by a carbon credit.

Trust design can vary widely depending on how the grantor structures the fund. Key design features of a trust include the timepoint at which the trust assumes non-permanence risk, how initial fees are invested and managed to grow in value, under what circumstances the trustee may deploy assets, and how assets may be used to manage risk or compensate for reversals. Two defining features of carbon trust funds are their ability to increase in value over time and their legal continuity, which allows compensation for reversals to occur beyond the lifespan of any individual market actor or entity. This approach has also been termed an "emissions liability management trust" (25), a "permanence trust" (26), and a "permanence fund" (14).

Revenue from a trust could be used to support a variety of activities to reduce permanence vulnerabilities and lower non-permanence risk. For example, trust revenue could fund appropriate land management activities. Trust revenue could also be deployed to extend the guaranteed durability of a credit to a specified durability threshold, such as purchasing new credits in a **horizontal stacking** approach (see Purchasing Strategies) or funds could be used to purchase insurance.

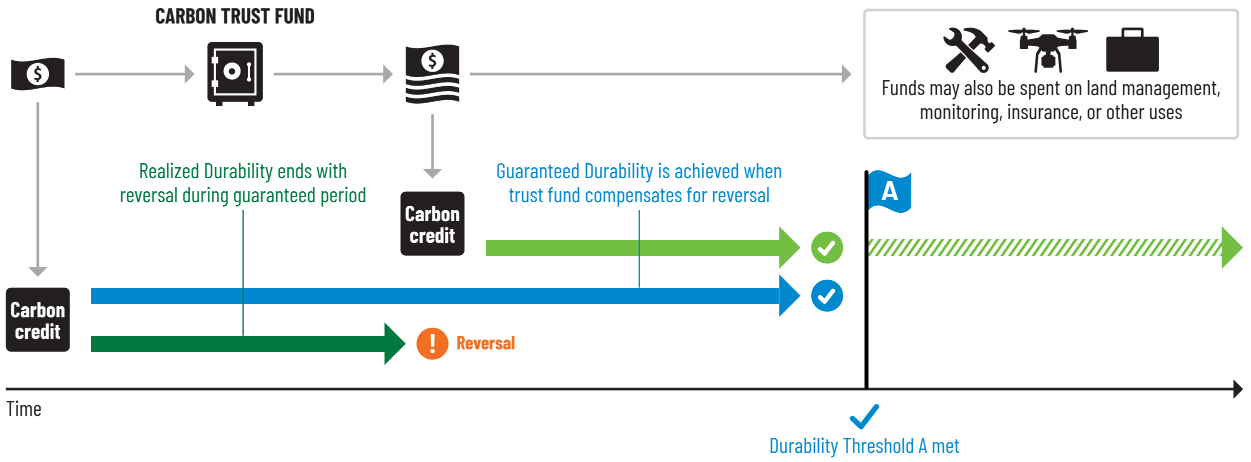
Setting up carbon trust funds requires both ex ante and ex post financial and risk assessments. Trust grantors must determine an appropriate fee for credits entering the trust to generate sufficient revenue to reliably manage and address permanence vulnerabilities. This requires financial modeling of projected future costs and timelines for expenditures. Ex post assessments are required to quantify carbon storage, carbon loss, and the amount of necessary compensation.

Because this approach is newly emergent in the carbon market, important questions remain about its implementation and potential impact. Market actors are currently conducting pilot and feasibility studies to address some of these questions (27,28). A primary consideration is how the grantor designs the trust to ensure long-term viability and achievement of intended outcomes. These design elements will likely need to be codified in compliance or voluntary standards, though overly restrictive rules may unintentionally limit the trustee's future flexibility and reduce the trust's effectiveness. For example, if trust funds are restricted to purchasing only certain types of credits and those credits are unavailable, the trust may be unable to compensate for reversals or purchase new credits at the end of a credit's durability period.

Second, it remains unclear which entities could serve as independent trustees and how such entities would be established within existing carbon markets. Market actors are exploring the characteristics that would make an institution suitable to manage a carbon trust fund. In compliance markets, a regulatory agency could reasonably serve as the trustee; in voluntary markets, however, the appropriate choice is less clear and would require further consideration. Identifying institutions and procedures that ensure transparency and independent assessment of financial modeling and non-permanence risk will be critical to ensuring confidence in this approach.

Finally, trust funds face the risk of insolvency if financial models underestimate the resources required to compensate for future reversals, insufficient funds are set aside, or investment strategies do not generate desired revenues. Trusts may mitigate this risk through active asset management and the strategic use of short-term insurance during periods of elevated risk, allowing the bulk of trust assets to continue generating returns. Because major capital drawdowns will typically occur following a large reversal or significant increase in vulnerability, this structure allows trusts to maximize investment performance in the interim while maintaining capacity to compensate when non-permanence risk is realized.

Figure 5: Carbon Trust Fund



PURCHASING STRATEGIES

Purchasing strategies manage non-permanence risk by coordinating credit purchases to ensure carbon storage through a desired durability threshold. This can be achieved by purchasing credits in excess of a climate mitigation claim, making ongoing purchases at the end of a credit's guaranteed durability, or replacing reversed credits. Some buyers refer to these stacks as portfolios, not to be confused with the portfolio design of the risk-weighted accounting approach (see Accounting Strategies). **Vertical stacking**[a] and horizontal stacking are two purchasing approaches discussed in this paper.

VERTICAL STACKING

Vertical stacking is a purchasing approach where a buyer intentionally overpurchases carbon credits, creating a "stack" whose total volume exceeds the buyer's **target credit volume.** The intention is to purchase a stack of credits whose realized durability will last through the buyer's desired durability threshold. By overpurchasing upfront, the buyer preemptively compensates for potential future reversals past the guaranteed durability period. As long as a reversal does not reduce the cumulative carbon credit volume below the target credit volume, the claim remains intact. Vertical stacking increases the likelihood that the realized durability of some credits in the stack will have reached the durability threshold in an ex post assessment (31).

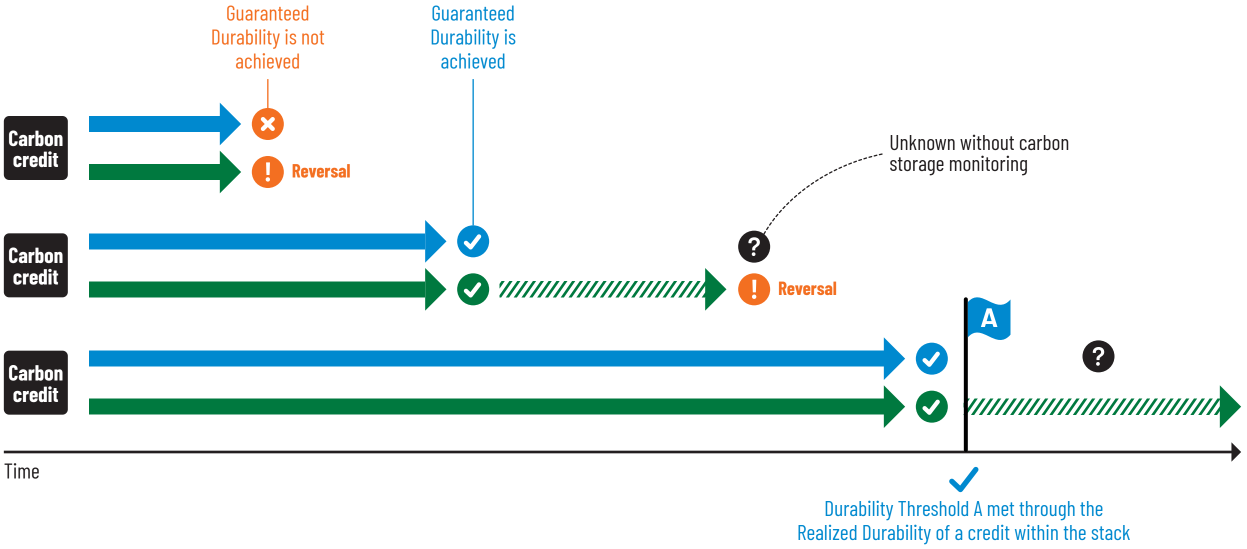
Vertical stacking reduces non-permanence risk by distributing non-permanence risk across multiple carbon credits. Similar to buffer pools or portfolio accounting, buyers can further reduce risk by stacking credits from diverse mitigation activities, project developers, or standards bodies, thereby reducing the likelihood that shared permanence vulnerabilities lead to concurrent reversals. The stack may be composed of credits with variable guaranteed durabilities and the buyer may leverage risk assessments to construct the stack, though not always. Unlike buffer pools or risk-weighted accounting approaches, however, vertical stacking relies on a one-time, initial purchase rather than ongoing replenishment of credits or active portfolio management.

As with many of the approaches covered in this paper, vertical stacking relies on ex ante estimates of the likelihood and magnitude of future reversals to determine the size of a "large-enough" stack. Because empirical data on reversal frequency and magnitude is sparse, estimates of over-purchasing factors can be challenging and underscores the need for improved transparency and data on non-permanence risk.

---

[a] Note, the term "stacking" can refer to multiple distinct activities in carbon market discourse. Some market actors seek to "stack" multiple ecosystem service benefits, and ideally benefit payments, that might arrive from a single activity, such as reforestation activities that store carbon, provide habitat for wildlife, and protect drinking water supplies (29). Other market actors seek to "stack" multiple climate mitigation activities at the same site to increase total carbon stocks (30).

Figure 6: Vertical Stacking



Additionally, if the credits in the stack are supplied from a single project and the project fails, the stack would fail entirely. Some market actors, such as ratings agencies, have calculated "overpurchasing factors" to guide buyers in determining stack purchases (32). For example, a buyer might purchase several lower-rated credits in lieu of a single high-rated credit to meet the same durability threshold.

With vertical stacking, the buyer assumes all non-permanence risk not addressed through other approaches, such as buffer pools. If reversals exceed expectations or the initial credit stack proves insufficient to meet the intended durability threshold, the buyer must purchase additional credits to maintain the claim. Vertically stacking therefore requires substantial upfront capital and sufficient market availability of eligible credits, but if credits increase in price through time, vertical stacking may reduce total long-term costs for a buyer relative to implementing a horizontal stacking approach.

To maintain confidence in the vertical stack, buyers must also assume monitoring responsibilities after the end of a credit's guaranteed durability period, although there is presently no enforcement for this activity. However, if a buyer purchases a larger stack than necessary—which could happen if there are relatively few reversals of stacked credits than predicted—then the buyer will have spent more money than necessary to fulfill their climate mitigation claims.

HORIZONTAL STACKING

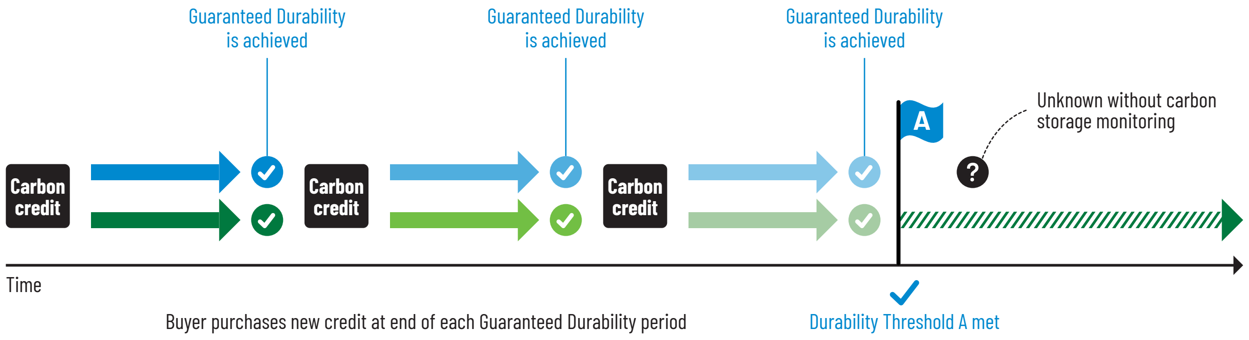
Horizontal stacking is a purchasing approach wherein a buyer purchases new carbon credits at the end of the guaranteed durability period or after a reversal occurs to extend the realized durability of a tonne of stored carbon dioxide. As long as the buyer continues to make sequential purchases of credits, carbon storage is sustained. Horizontal stacking creates a mechanism for a buyer to extend the realized durability of their credit stack. Horizontal stacking operates on ex post assessments of durability that allow for continued extension of durability thresholds. This may result in more secure and verifiable carbon storage.

The use of horizontal stacking of carbon credits has existed since at least 2000, when it was conceptualized as "carbon renting" in Kyoto Protocol discussions (33). The UN Clean Development Mechanism classified afforestation and reforestation credits as "temporary" or "expiring" credits and required buyers to replace these credits at prespecified points in the future (34,35). However, weak buyer demand and policy restrictions, including the EU's ban on temporary credits, limited the adoption of this approach (34). There is now renewed interest in horizontal stacking as a way to invest in credits today with shorter estimated durability and eventually replace them with credits with longer estimated durability, reflecting broader exploration of the complementary approaches discussed in this paper (5,31,36).

Buyers using horizontal stacking compensate for reversals or for the expiration of a credit's guaranteed durability by purchasing replacement credits. After the guaranteed durability period ends, the buyer assumes all non-permanence risk. Critically, because horizontal stacking is based on sequential repurchases, it requires continued engagement of the credit buyer to reach the desired durability threshold. Longer thresholds (i.e., multiple decades) carry increased uncertainty about a buyer's continued engagement in purchasing credits. Numerous developments could interfere with initial intentions, such as changes in company viability or ownership and changing policy environments. If the buyer stops purchasing credits prior to the desired durability threshold, the climate mitigation claim may no longer be valid.

From a market perspective, horizontal stacking generates consistent demand for credits through time with reliable projected purchases and thus requires a consistent supply of credits. Horizontal stacking could increase the stability of future demand for credits. From the buyer's perspective, a significant limitation of the horizontal stacking approach is the uncertainty of total costs and timing of reversals that will require new stack purchases. If prices of credits increase through time, buyers' carbon crediting budgets will need to increase to continue purchasing credits for the purchase policy, claim, or other intended use case. It may also be unclear whether a buyer will maintain the institutional ability and mandate to continue horizontal stacking for the full durability threshold.

Figure 7: Horizontal Stacking



ACCOUNTING STRATEGIES

Accounting strategies incorporate non-permanence risk in credit values by requantifying carbon credits based on a credit's estimated durability, non-permanence risk, and/or the climate impact of carbon storage. Risk-weighted and **time-weighted** accounting approaches are discussed in this paper.

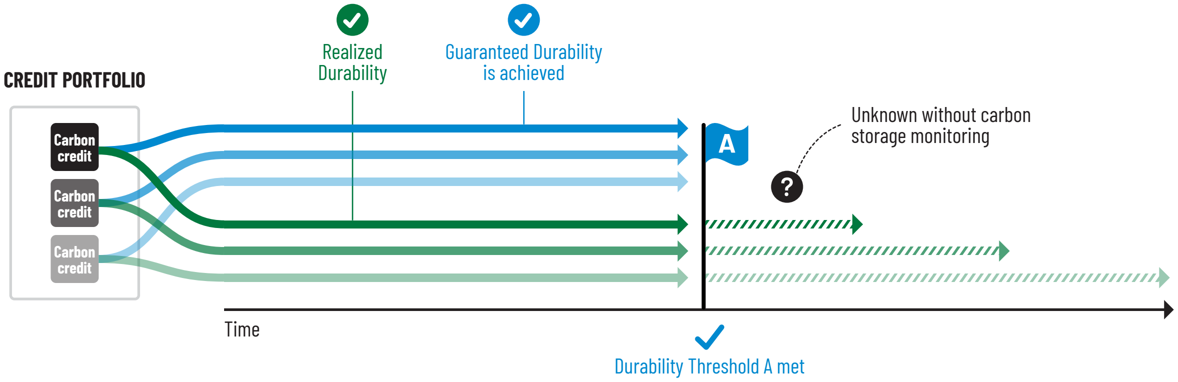
RISK-WEIGHTED ACCOUNTING

Risk-weighted accounting employs approaches from financial risk management to create balanced and diversified portfolios of carbon credits or carbon projects that minimize overall risk. Generally, portfolios are managed by third-party companies that evaluate and weigh the risk of individual carbon projects or credits and then use those risk weightings to create a large portfolio of credits that balance cost and risk. Buyers may purchase "shares" or a new unit of blended credits of the portfolio. Risk-weighted accounting does not directly address a credit's permanence vulnerabilities but, like buffer pools, spreads risk among many buyers by sourcing a variety of credits. If risk-weighted accounting successfully reduces non-permanence risks across the portfolio and the portfolio is managed through time, this approach may deliver longer realized durability across the portfolio. Just as diversifying stocks can reduce volatility, diversifying a carbon credit portfolio reduces exposure to permanence vulnerability associated with a specific project, geography, management team, or sector.

Portfolio management companies or external rating agencies typically perform risk-weighted accounting assessments, which can occur before or after credit issuance. Non-permanence risk is a major risk addressed in most accounting portfolios, but there are a variety of other crediting risks, such as the likelihood that a project will have non-additional credits, or other factors, such as the impact on local communities, that a manager may wish to weight in their risk-weighted accounting method. These management companies may either assist buyers in building customized portfolios of credits or sell their own unique portfolio-backed credits that are a composite, curated mix of the management company's larger "fund" of credits.

A portfolio accounting approach provides buyers the opportunity to diversify across project types that offer a range of estimated durabilities. Buyers can design portfolios that combine credits with lower estimated durabilities but lower costs and credits with higher estimated durabilities but higher costs to satisfy budgetary constraints and meet other potential objectives like benefits to local communities, indigenous peoples, and biodiversity. For example, a company that purchases carbon credits generated from an improved forestry management project with high fire risk may combine this purchase with credits from a project with lower fire risk. Additionally, with active portfolio management, buyers can strategically transition their investments over time. For example, a buyer could start with a portfolio composed of a majority of credits with lower estimated durabilities and

Figure 8: Risk-Weighted Accounting



could shift the composition of the portfolio through time to include a higher proportion of credits with higher estimated durabilities as they become increasingly available and affordable.

When a reversal occurs within a risk-weighted accounting approach, buffer pools managed by standards bodies serve as the first line of defense to compensate for the emitted carbon. However, if the buffer pool is inadequately stocked, the portfolio contains credits without buffer pools, or other non-covered risks such as methodology changes or reputational issues arise, portfolio accounting can act as a second layer of risk management on top of this existing protection. When the composition of a portfolio of credits changes—either owing to a replacement credit for a reversal or the portfolio manager decides to sell particular credits—the portfolio manager must rebalance the portfolio through additional credit purchases or sales to maintain their intended portfolio composition and risk profile.

Borrowing investing and accounting approaches and terminology from established financial markets may increase accessibility and appeal to buyers. In addition, portfolio management firms bear the burden of navigating the complexities of the carbon market, relieving the client-buyer of those responsibilities. An influx of buyers investing in diversified project types and sectors may lead to substantial market growth, more investment in new technologies, and increased harmonization between mitigation activities.

There are some challenges to portfolio accounting. Notably, it relies heavily on accurate ex ante assessments of individual project permanence vulnerabilities. Market actors are still debating the best methods for determining non-permanence risk and estimated durabilities, leaving room for continuing disagreements about whether portfolios are reliably accounting for risk. Additionally, risk assessment methods are generally proprietary to the rating agency or portfolio management company, although this could change with some market actors in the process of developing non-proprietary approaches (14,37,38). Moreover, traditional financial markets are heavily regulated and use strict standards to assess and report risk, but presently voluntary carbon credits and markets are not regulated as financial instruments. Risk assessment outcomes in voluntary markets are essentially proprietary to the external rating agency or portfolio management company and are not necessarily comparable or verifiable. Because rating agencies review methods are opaque, project developers and market analysts have noted inconsistency in ratings between similar projects and inconsistent ratings of the same project by different rating agencies (39). Hence, as with all other strategies discussed here, independent and transparent non-permanence risk data are likely to be quite important for improving trust and integrity.

TIME-WEIGHTED ACCOUNTING

Time-weighted accounting approaches estimate the time-integrated climate impact of carbon storage or emission reductions over predetermined periods. These approaches initially emerged in discussions about the Kyoto Protocol's Clean Development Mechanism (40). In other words, these methods attempt to equate the climate impact of fossil fuel emissions with the climate impact of avoided emissions or removals that may have different estimated durabilities. Time-weighted accounting approaches are complex to implement and have become highly contentious (41,42).

Applying time-weighted approaches first requires creating a new and distinct unit of carbon measurement that tracks both the amount of carbon stored and the duration of storage. The most common of these units is the "tonne-year," representing a tonne of carbon dioxide equivalent kept out of the atmosphere for one year. For this reason, this approach is sometimes referred to as "tonne-year" accounting. However, any combination of the amount of carbon stored over a specific period could also constitute a time-weighted storage unit.

In addition to creating a new unit, these approaches must also determine the climate impact of carbon dioxide emissions for a designated time horizon. This accounting step is complex due to the biophysical processes that reduce carbon dioxide emissions in the atmosphere over time. It is also contentious because it requires policy decisions about which climate impacts to prioritize over what policy time horizons (42,43). The chosen time horizon indicates the timepoint beyond which the impacts and benefits of carbon storage cease to be valued, in turn affecting the present estimated climate benefit of an activity. Shorter time horizons ignore long-term impacts of carbon dioxide emissions, meaning that buyers can purchase fewer time-weighted credits to neutralize a tonne of carbon dioxide equivalent emissions.

Since their inception, most time-weighted approaches have focused on tracking the climate impact of **radiative forcing**, or the amount of heat trapped on earth by increasing atmospheric gas concentrations. Because carbon dioxide is slowly removed from the atmosphere by the earth's oceans and vegetation, the "cost" of an emission can be estimated by summing the amount of carbon dioxide in the atmosphere for each year over the chosen time horizon. Once the cost of the emission is estimated, then it can be used to create an equivalency ratio of the number of time-weighted units (for example, tonne-years) required to offset the estimated cost of the emission. To date, these equivalency ratios have ranged between 30-150 (40,44,45), meaning it could, for example, require 30 to 150 tonne-years of storage to offset one tonne of emissions.

Some time-weighted accounting methods also incorporate economic valuations of temporary carbon storage. This typically involves using the social cost of carbon, which quantifies the economic impact of an additional tonne of emissions (46), and economic discount rates, wherein the future rate of return on the investment is used to calculate its present value (47). Under this method, avoided emissions today are considered to have higher economic value than avoided emissions at a later date. Proponents of including economic valuations in time-weighted accounting methods argue that discounting theory suggests that the economic cost of deploying mitigation activities today is lower than the economic costs of delaying such actions (47).

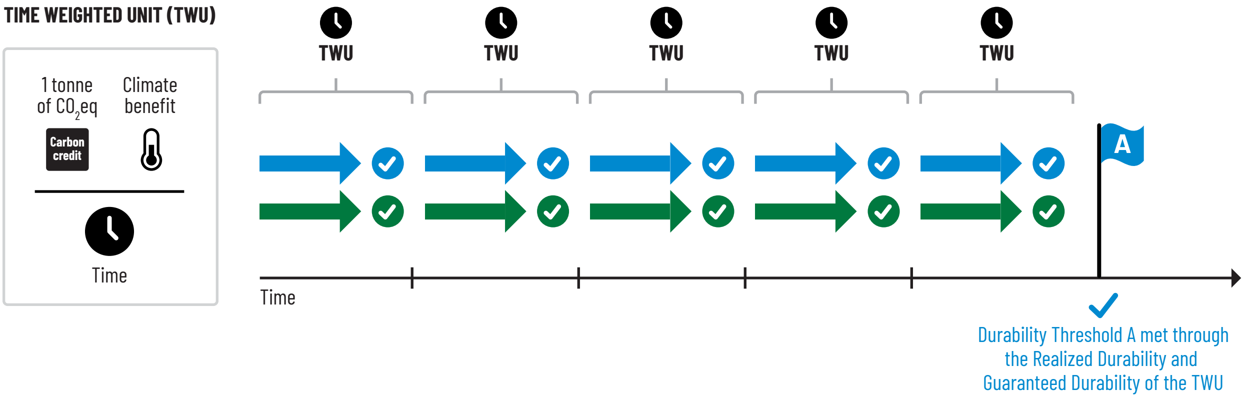
However, critics argue that by emphasizing the economic value of mitigation actions rather than of just the amount of carbon dioxide in the atmosphere, these economic time-weighted accounting methods disrupt the physical equivalency relationship between carbon storage and climate impacts (42). In addition, including a social cost of carbon and a discount rate introduces further value judgments while selecting a cost and rate at which to discount the future (42,48).

Time-weighted accounting approaches do not extend the estimated durability or lower non-permanence risk of a carbon credit. Rather, this family of accounting approaches handles non-permanence risk in the design of the new unit and the equivalency factor. If a buyer agrees with assumptions and decisions embedded in the time-weighted accounting method, they can purchase tonne-years of carbon that have already met their guaranteed durability period and not worry about future reversals. Thus, a benefit of time-weighted accounting is that the credit has no permanence vulnerability at its issuance.

Finally, time-weighted accounting approaches face an inherent trade-off with another credit integrity element: **additionality**. Time-weighted approaches frequently shorten the time period an activity must store carbon or reduce emissions, making them susceptible to claiming business as usual behavior as additional (41). For example, a landowner planning to harvest timber in the future may be able to generate short-term storage credits up until the intended harvest date. If the landowner always planned to harvest at a later date, those short-term credits are not additional. Therefore, implementing time-weighted accounting approaches will need to institute new additionality safeguards to prevent this gaming.

To date the market has largely rejected time-weighted accounting or heavily criticized its use (43,49,50,51). At present, the only major standards body that permits time-weighted accounting is the Climate Action Reserve. The Reserve's methods select a 100 year time horizon and assume the climate impact of a tonne of carbon dioxide emitted is equivalent to storing a tonne of carbon dioxide for 100 years (42). However, market actors and researchers continue to offer new ideas about how to incorporate time-weighted accounting into the market (9,45), given its potential to reduce or eliminate the need for durability guarantees.

Figure 9: Time-Weighted Accounting



COMPARING AND COMBINING APPROACHES

Meeting near-term climate targets requires rapid deployment of all available mitigation tools, including nature-based solutions that can deliver climate benefits today. However, using these tools at scale requires confronting and managing their inherent non-permanence risks. Market actors are rapidly rising to this challenge, generating new ideas and approaches to mitigate risks and ensure climate mitigation claims. As newer approaches gain more traction alongside buffer pools, we expect market actors to use combinations of these approaches to manage non-permanence risk of carbon credits. Rather than attempting to catalog or recommend all possible combinations of approaches, this section provides a general overview of how and why multiple approaches may interact to manage non-permanence risk in carbon crediting. We hope this taxonomy and framework will support deeper evaluations and guide the adoption and use of combined approaches.

Approaches differ in how they lower non-permanence risk: Some reduce permanence vulnerabilities that then reduce the likelihood of reversals, while others pool non-permanence risk across credits, projects, permanence vulnerabilities, and market actors to reduce the likelihood of a reversal nullifying a buyer's climate mitigation claim (Table 1). The choice of which approach or combination of approaches most appropriately manages non-permanence risk will depend on the buyer's or policy's specific goal, use case, or climate mitigation claim. For example, if a buyer is most interested in offloading their non-permanence risk and being compensated in the event of a reversal, then a risk-transfer strategy is likely sufficient. However if a buyer seeks to reach a durability threshold beyond a credit's guaranteed durability, they may want to use horizontal stacking to replace credits that have met their guaranteed durability period with new credits or a carbon trust to extend a purchased credit's guaranteed durability period. In addition, the effect of some approaches may fall into other strategy categories—risk-transfer, accounting differences, purchasing variations—depending on the market actor implementing the approach. For example, an entity that has been transferred non-permanence risk may use an accounting or purchasing strategy to manage that risk. One major limitation of all approaches is that they are each subject to institutional infrastructure that have variable lifespans, which may be shorter than some durability thresholds required by specific policies, use cases, or claims (22).

Nearly all carbon credits currently sold are backed by a buffer pool managed by a standards body, which compensates for unavoidable reversals and pools non-permanence risk across projects. However, concerns that some buffer pools may be insufficiently capitalized have prompted interest in improving risk assessment data and complementary approaches that can reinforce guaranteed durability or support climate claims that extend beyond guaranteed durability periods. These approaches work by extending a credit's estimated durability, reducing non-permanence vulnerabilities, delivering adequately capitalized buffer pools, or compensating for reversals should buffer pools fall short. Market actors may layer some of the approaches outlined in this paper on top of existing buffer pools to provide additional protection against non-permanence risk—a "belt and suspenders" strategy—while others may explore using some of the approaches as partial or full replacements for traditional buffer pools (52).

Table 1: Comparison of prominent characteristics across non-permanence risk mitigation approaches. Evaluations assume that each approach is enacted responsibly to achieve climate mitigation goals.

	RISK-TRANSFER STRATEGIES			PURCHASING STRATEGIES		ACCOUNTING STRATEGIES	
	CREDIT BUFFER POOL	**INSURANCE**	**CARBON TRUST**	**VERTICAL STACKING**	**HORIZONTAL STACKING**	**RISK-WEIGHTED**	**TIME-WEIGHTED**
Decreases Non-Permanence Risk by Pooling Risk	Yes	Yes	Yes	Yes	No	Yes	No
Decreases Non-Permanence Risk by Decreasing Permanence Vulnerabilities	Indirectly	Indirectly	Indirectly	No	No	No	No
Primary Risk Holder	Buffer Pool Manager	Insurance Agency	Trust	Buyer	Buyer	Portfolio Manager	Credit Issuer
Buy-Side and/or Supply-Side Strategy	Supply	Both	Both	Buy	Buy	Supply	Both
Needs Transparent Risk Assessment to Implement	Yes	Yes	Yes	Yes	No	Yes	No
Number of Standards Bodies Implementing Approach*	7	1 (Pilot Phase)	1 (Pilot Phase)	NA	NA	0	1

*We assessed seven major standards bodies to determine whether their protocols incorporate any of the seven approaches as of April 2026. If at least one protocol from a given standards body included an approach, we counted that approach as "approved" by the standards body. These were selected because they represent the majority of nature-based carbon credit sales in the voluntary carbon market activity by both price and volume, according to Ecosystem Marketplace's State of the Voluntary Carbon Market (53). The standards reviewed were Verra Carbon Standard (VCS), American Carbon Registry, Gold Standard, Climate Action Reserve, Plan Vivo, UK Woodland Carbon Code, and Cercarbono.

CONCLUSION AND CALL TO ACTION

The approaches outlined in this paper demonstrate a growing and diverse toolkit for addressing non-permanence risk in carbon markets. These approaches may allow market actors on both the supply and demand side to complement existing buffer pool approaches and explore new ways to reduce, manage, and allocate non-permanence risk. By organizing these approaches into three overarching strategies—risk-transfer, purchasing, and accounting—and introducing shared terminology for discussing durability, this paper aims to provide a common framework that market actors can use to support nuanced debates, evaluate options, test combinations, make more informed choices, and most importantly, take action to mitigate climate change now. With that aim, we encourage wide adoption of the glossary of terms—particularly those around the facets of durability—provided here.

Our taxonomy is not intended to prescribe a single solution, but to synthesize and organize approaches to support the durability of carbon storage. We recommend these approaches be adopted, refined, and stress-tested across contexts and use cases. We highlight the strengths and limitations of individual approaches “in theory,” but we hope to stimulate more analysis that can assess the political, economic, and practical feasibility of approaches, both independently and in combination. There remains much to learn as market actors discuss, pilot, and begin to implement these approaches.

Central to all efforts of understanding the efficacy of these approaches will be improved, transparent, and comparable non-permanence risk data across ecosystems, regions, and market pathways.

This suite of approaches offers an opportunity to more equitably share risk among market actors, appropriately price durability, align durability thresholds with differing policy and climate goals, and avoid perpetuating intergenerational or geographic inequities through inadequate risk management. We encourage market participants, policymakers, and researchers to use this framework as a starting point for experimentation, evaluation, and ultimately, more credible and effective deployment of natural climate solutions.

Image: Balnyes, Shutterstock.com

APPENDIX I GLOSSARY OF TERMS

Accounting Strategy: A durability strategy that involves quantifying the value of a carbon credit based on a credit's estimated durability, non-permanence risk, and/or the climate impact of carbon storage. There are two accounting mechanisms: risk-weighted accounting and time-weighted accounting.

Additionality: A property relating to carbon credits such that "the greenhouse gas (GHG) emission reductions or removals from the mitigation activity shall be additional, i.e., they would not have occurred in the absence of the incentive created by carbon credit revenues" (54).

Avoidable (Intentional) Reversals: Reversals caused by intentional activities that release stored carbon in the project area (e.g., harvesting), also known as an intentional reversal (55).

Atmosphere: The layer of gas and aerosols that extend up from Earth's surface into interplanetary space (56).

Buyer: An individual or organization who purchases carbon credits**.**

Carbon Credit: A tradeable instrument that is issued by a carbon-crediting program, representing a greenhouse gas emission reduction to, or removal from the atmosphere equivalent to one metric tonne of carbon dioxide. This is calculated as the difference in greenhouse gas emissions or removals from a baseline scenario to the emissions or removals occurring under the mitigation activity, and any adjustments for leakage. The carbon credit is uniquely serialized, issued, tracked and retired or administratively cancelled by means of an electronic registry operated by an administrative body, such as a carbon-crediting program (54).

Carbon-Crediting Program: A standard-setting program that registers carbon projects and issues, tracks, and retires carbon credits (54).

Carbon Dioxide Equivalent (CO_2e): The number of metric tons of carbon dioxide (CO_2) emissions with the same global warming potential as one metric ton of another greenhouse gas and is calculated using this formula (57).

$$CO_2e=\sum_{i=1}^{n} GHG_i \times GWP_i$$

CO_2e = Carbon dioxide equivalent, metric tons/year. GHGi = Mass emissions of each greenhouse gas, metric tons/year. GWPi = Global warming potential for each greenhouse gas. n = The number of greenhouse gases emitted.

Carbon Project: A project which seeks to reduce or remove carbon dioxide emissions or other greenhouse gas, as measured in carbon dioxide equivalent (CO_2e) (58).

Carbon Sink: Any process, activity, or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere (59).

Carbon Pool: A natural reservoir of carbon on or around Earth. Carbon markets generally recognize the following carbon pools as places to store carbon: the atmosphere, the ocean, terrestrial ecosystems (including vegetation and soils), aquatic freshwater ecosystems (including vegetation and soils), and geological (subterranean) zones.

Carbon Trust Fund: A risk-transfer mechanism where a fee is deposited into a financial trust managed by an independent market entity taking on permanence vulnerabilities. The associated fees generate revenue to support activities that monitor and reduce non-permanence risks and/or invest in other durability strategies or credits for stacking with negligible risk of reversal. These trusts may also be called permanence funds or permanence trusts (14).

Climate (Change) Mitigation Claim, Claimed Climate Benefit: An assertion made by the claimant (most often a carbon credit buyer) of the impact that a mitigation activity (as represented by a carbon credit) has on limiting the severity of climate change. The most common climate change mitigation claim in the market today is fossil fuel neutralization.

Credit Buffer Pool: A risk-transfer mechanism in which a portion of carbon credits generated from carbon projects are withheld from sale and are used to replace credits if a reversal occurs.

Cumulative Radiative Forcing: A way of measuring the future impact of GHG emissions: instantaneous radiative forcing refers to an instantaneous change in net radiative flux (in W m−2) due to an imposed change. The cumulative radiative forcing is an integral of radiative forcing over a given time and is used to calculate the contribution to the global mean net radiative forcing due to greenhouse gases and aerosols from various regions (3,60).

Durability: A metric for permanence that comprises two components: the timeframe credited carbon dioxide equivalent is held out of the atmosphere; and the likelihood the carbon dioxide equivalent will remain stored for this timeframe.

Durability Strategy: Approaches that market actors can deploy to improve the realized durability of a carbon credit.

Durability Threshold: A length of time that a tonne of carbon dioxide equivalent, represented by a carbon credit, must remain out of the atmosphere to meet a particular policy goal, use case, or claim. Different policy frameworks or standards may require different durability thresholds for meeting different climate goals.

Permanence obligations and permanence periods are sometimes used synonymously.

For example, the California Air Resources Board sets a durability threshold of 100 years while the Australian Carbon Credit Unit Scheme sets a durability threshold of either 25 or 100 years (61).

Estimated Durability: A projected estimate of the length of time a tonne of carbon dioxide equivalent will remain stored out of the atmosphere based on risk assessments of carbon loss from a given carbon sink. Estimated durability may be calculated at different scales–for example, a single forest stand or for a jurisdiction–and for different carbon pools.

Ex ante: Based on predicted or expected results; forecast, anticipated (62).

Ex post: Based on or determined by actual results, rather than expectations; calculated retrospectively (63).

Greenhouse Gas: Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth’s surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect (54).

Guaranteed Durability: The length of time a tonne of carbon dioxide equivalent is guaranteed to remain out of the atmosphere by an entity, often through contractual or legal means.

Horizontal Stacking: A purchasing mechanism where a buyer purchases new carbon credits at the end of the guaranteed durability period or if a reversal occurs to increase the realized durability of a tonne of stored carbon dioxide equivalent.

Insurance: A risk-transfer mechanism in which an insurance provider is contractually obligated to supply financial or carbon credit equivalent compensation in the event of a covered loss, including a reversal.

Mitigation Activity: An activity that reduces anthropogenic emissions of a GHG or enhances removals by sinks relative to GHG emissions or removals in the activity's baseline scenario and seeks registration and issuance of carbon credits under a carbon-crediting program. The term refers to activities that may be implemented at different scales, including projects, programmatic approaches, policies, jurisdictional REDD+ programs, and other interventions. They may also be implemented at one or more sites (54).

Natural Climate Solution (NCS): Deliberate human actions that protect, restore, and improve management of forests, wetlands, grasslands, oceans, and agricultural lands to mitigate climate change. NCS should have no net negative impact on food and fiber supply and no net harm to biodiversity, while ensuring actions are implemented in socially and culturally responsible ways (1).

Non-Permanence Risk: The likelihood a reversal of a given magnitude will occur.

Permanence: A concept in carbon markets that describes the intended length of time that greenhouse gases are kept out of the atmosphere as a result of a mitigation activity with enough certainty to support a claimed climate benefit.

Permanence Vulnerability: A characteristic, such as ecology, location, or management, of a carbon credit that could lead to a reversal.

Project Developer (Proponent): An individual or organization that may design, develop, and/or implement climate mitigation activities to produce carbon credits. Also known as the Mitigation Activity Proponent (54).

Purchasing Strategy: A durability strategy where a buyer selectively purchases carbon credits to extend the realized durability of a claim. There are two purchasing mechanisms: horizontal stacking, and vertical stacking.

Realized Durability: The length of time a tonne of carbon dioxide equivalent remained out of the atmosphere. Importantly, realized durability can only be known ex post or when a reversal occurs.

Reversal: A net loss in the storage of carbon dioxide equivalent calculated across all applicable greenhouse gas reservoir(s) over a period of time in a defined area.

Risk-Transfer Strategy: A durability strategy that reallocates non-permanence risks from one market actor to another market actor. Generally, risk-transfer strategies attempt to lower financial or climate risk by pooling risk across a larger number of projects or market actors. There are three risk-transfer mechanisms: credit buffer pools, insurance, and carbon trust funds.

Risk-Weighted Accounting: An accounting mechanism where a market actor employs approaches from financial risk management to create balanced and diversified portfolios of carbon credits or carbon projects that minimize overall risk.

Standards Bodies, Registries, Crediting Programs: Entities or organizations that act as market regulators. Standards bodies may publish standards, methodologies, and/or protocols, issue and certify carbon credits, and safeguard the quality and claims of carbon credits.

Target Credit Volume: The number of credits a buyer purchases to match the quantity of CO_2e it is motivated to offset or remove from the atmosphere.

Time-Weighted Accounting: An accounting mechanism that estimates the time-integrated climate impact of carbon storage or emission reductions over predetermined periods.

Unavoidable (Unintentional) Reversal: A reversal over which the project proponent (or developer) has no control. Examples include natural disasters such as hurricanes, earthquakes, flooding, drought, fires, tornados and winter storms, and human-induced events such as acts of terrorism, crime, or war. Encroachment by outside actors (e.g., logging, mining, or fuelwood collection) are considered unavoidable when demonstrably unforeseeable and out of the project proponent's control (64).

Vertical Stacking: A purchasing mechanism where a market actor initially over-purchases a volume of carbon credits whose guaranteed durability sums to an amount greater than the buyer's total estimated emissions for a given time period.

Image: Damsea, Shutterstock.com

REFERENCES

1 P. W. Ellis *et al.*, *Nat. Commun.* **15**, 547 (2024).

2 D. C. Marvin, B. M. Sleeter, D. R. Cameron, E. Nelson, A. J. Plantinga, *Sci. Rep.* **13**, 19008 (2023).

3 IPCC, *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022; https://dx.doi.org/10.1017/9781009157926).

4 M. R. Allen *et al.*, *Nature*. **638**, 343–350 (2025).

5 C. Brunner, Z. Hausfather, R. Knutti, *Commun. Earth Environ.* **5**, 645 (2024).

6 J. Sanderman, T. Hengl, G. J. Fiske, *Proc. Natl. Acad. Sci.* **114**, 9575–9580 (2017).

7 A. M. Raiho *et al.*, *Science*. **376**, 1491–1495 (2022).

8 E. Gorham, C. Lehman, A. Dyke, D. Clymo, J. Janssens, *Quat. Sci. Rev.* **58**, 77–82 (2012).

9 H. D. Matthews *et al.*, *Commun. Earth Environ.* **3**, 65 (2022).

10 W. R. L. Anderegg *et al.*, *Nature*. **643**, 1214–1222 (2025).

11 C. Streck *et al.*, *Clim. Policy*. **26**, 493–501 (2026).

12 A. K. Kern *et al.*, *Quat. Sci. Rev.* **299**, 107867 (2023).

13 The Integrity Council for the Voluntary Carbon Market, in *Core Carbon Principles Assessment Framework and Procedure* (The Integrity Council for the Voluntary Carbon Market, 2024; https://icvcm.org/assessment-framework/).

14 Continuous Improvement Work Program, "Continuous Improvement Work Program report: Permanence" (The Integrity Council for the Voluntary Carbon Market, 2025).

15 Verified Carbon Standard Version 5, VCS Standard Version 5.0 (2025), (available at https://verra.org/programs/verified-carbon-standard/verified-carbon-standard-version-5/).

16 A. Busch, N. Kampman, in *Geological Carbon Storage: Subsurface Seals and Caprock Integrity* (American Geophysical Union, Washington D.C., 2018; https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119118657.ch14), *Geophysical Monograph Series*, pp. 283–303.

17 M. R. Allen *et al.*, *Npj Clim. Atmospheric Sci.* **5**, 5 (2022).

18 S. Solomon, G.-K. Plattner, R. Knutti, P. Friedlingstein, *Proc. Natl. Acad. Sci.* **106**, 1704–1709 (2009).

19 W. R. L. Anderegg, Permanence, buffer pools, and forest carbon projects (2025), (available at https://yff.yale.edu/speaker/william-anderegg-and-liz-guinessey).

20 L. Eash, M. A. Bradford, E. E. Oldfield, S. M. Ogle, S. E. Kuebbing, *Environ. Res. Lett.* **20**, 124065 (2025).

21 G. Badgley *et al.*, *Front. For. Glob. Change*. **5** (2022), doi:10.3389/ffgc.2022.930426.

22 W. R. L. Anderegg, A. T. Trugman, G. Vargas G., C. Wu, L. Yang, *Glob. Change Biol.* **31**, e70251 (2025).

23 C. Wu *et al.*, *Nat. Geosci.* **16**, 422–429 (2023).

24 B. K. Haya *et al.*, "Quality assessment of REDD+ carbon credit projects" (Berkley Carbon Trading Project, 2023), (available at https://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/berkeley-carbontrading-project/REDD+).

25 M. Roston, A. Seiger, T. Heller, *Oxf. Open Clim. Change*. **3**, kgad006 (2023).

26 N. Truitt, L. Riley, A Trust for Permanence: Enabling a New Generation of Permanent Nature-Based Credits in the Voluntary Carbon Market (2025), (available at https://www.forestfoundation.org/permanence-trust/).

27 Verified Carbon Standard Version 5, VCS Program Durability Pilot to Address Non-permanence Risk: Overview and Application Process (2025), (available at https://verra.org/wp-content/uploads/2025/12/VCS-Program-Durability-Pilot-Overview-and-Application-Process-1.pdf).

28 American Forest Foundation, Carbon market stakeholders launch feasibility study, advisory group on new permanence framework. *Fam. For. Blog* (2025), (available at https://www.forestfoundation.org/why-we-do-it/family-forest-blog/carbon-market-stakeholders-launch-feasibility-study-advisory-group-on-new-permanence-framework/).

29 D. Cooley, L. Olander, "Stacking Ecosystem Services Payments: Risks and Solutions" (NI WP 11-04, Nicholas Institute for Environmental Policy Solutions, Durham, NC, 2011), (available at https://nicholasinstitute.duke.edu/sites/default/files/publications/stacking-ecosystem-services-payments-paper.pdf&sa=D&source=docs&ust=1775152409407757&usg=AOvVaw3jbptkwNOOzN-hu2qYOSH6E).

30 New ERF method and 2022 priorities announced. *Hon Angus Taylor MP* (2021), (available at https://www.minister.industry.gov.au/ministers/taylor/media-releases/new-erf-method-and-2022-priorities-announced).

31 B. Cabiyo, Accounting for short-term durability in carbon offsetting. *Carbon Direct* (2022), (available at https://www.carbon-direct.com/insights/accounting-for-short-term-durability-in-carbon-offsetting).

32 S. Cross, Credible Carbon Claims Using the BeZero Carbon Rating. *BeZero Carbon* (2023), (available at https://bezerocarbon.com/insights/how-to-make-credible-claims-using-the-bezero-carbon-rating).

33 G. Marland, K. Fruit, R. Sedjo, *Environ. Sci. Policy*. **4**, 259–268 (2001).

34 M. Gillenwater, S. Seres, *Greenh. Gas Meas. Manag.* **1**, 179–203 (2011).

35 C. S. Galik, B. C. Murray, S. Mitchell, P. Cottle, *Mitig. Adapt. Strateg. Glob. Change*. **21**, 101–118 (2016).

36 CarbonPlan, Permanence calculator (2026), (available at https://carbonplan.org/research/permanence-calculator).

37 Carbon at Risk, Portfolio Risk Management for Carbon Markets. *Carbon Risk* (2026), (available at https://www.carbonatrisk.org).

38 United Nations Framework Convention on Climate Change, "Article 6.4 Activity Standard for Projects" (A6.4-STAN-AC-002, 2025).

39 B. Faecks, G. Dufrasne, "Rating the Raters: Assessing the quality of carbon credit rating agencies" (Carbon Market Watch, 2023), (available at https://carbonmarketwatch.org/wp-content/uploads/2023/09/CMW_Policybriefing_rating_raters-v2.pdf).

40 IPCC, "2.3.6.3 Equivalence Time and Ton-Years," *Land Use, Land-Use Change and Forestry* (Vienna, Austria, 1998), (available at https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=74).

41 J. Crook, Carbon Market Watch response to Verra's proposed "tonne-year accounting" method. *Carbon Mark. Watch* (2022), (available at https://carbonmarketwatch.org/publications/carbon-market-watch-response-to-verras-proposed-tonne-year-accounting-method/).

42 F. Chay *et al.*, Unpacking ton-year accounting. *CarbonPlan* (2022), (available at https://carbonplan.org/research/ton-year-explainer).

43 G. Badgley, F. Chay, J. Freeman, K. Martin, Problems with Quebec's new reforestation offsets protocol. *CarbonPlan* (2023), (available at https://carbonplan.org/research/ton-year-quebec).

44 H. D. Matthews, Accounting for storage time in carbon crediting systems (2025), (available at https://yff.yale.edu/speaker/damon-matthews-and-kristina-hughes).

45 H. D. Matthews, K. Zickfeld, A. Koch, A. Luers, *Nat. Commun.* **14**, 5485 (2023).

46 W. D. Nordhaus, *Proc. Natl. Acad. Sci.* **114**, 1518–1523 (2017).

47 Z. Parisa, E. Marland, B. Sohngen, G. Marland, J. Jenkins, *For. Policy Econ.* **144**, 102840 (2022).

48 S. H. Arcusa, K. S. Lackner, *Environ. Sci. Policy*. **173**, 104223 (2025).

49 Verra, Verra Defers Updates to the VCS Program (2022), (available at https://verra.org/verra-defers-updates-to-the-vcs-program/).

50 Z. Parisa, M. Nova, An update from NCX co-founders Zack Parisa and Max Nova. *Nat. Cap. Exch.* (2023), (available at https://ncx.com/blog/an-update-from-ncx-co-founders-zack-parisa-and-max-nova-2/).

51 Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs, Québec's method for creating permanent offset credits based on climate benefits derived from CO_2 removal - Summary Sheet (2026), (available at https://www.environnement.gouv.qc.ca/changements/carbone/credits-compensatoires/methode-quebecoise-credits-retrait-co2-en.pdf).

52 Verra, Verra to Pilot Innovative Approaches to Addressing Durability (2025), (available at https://verra.org/verra-to-pilot-innovative-approaches-to-addressing-durability/).

53 Forest Trends' Ecosystem Marketplace, "2025 State of the Voluntary Carbon Market" (Forest Trends Association, Washington D.C., 2025), (available at https://www.ecosystemmarketplace.com/publications/2025-state-of-the-voluntary-carbon-market-sovcm/).

54 The Integrity Council for the Voluntary Carbon Market, in *Core Carbon Principles Assessment Framework and Procedure* (The Integrity Council for the Voluntary Carbon Market, 2024; https://icvcm.org/assessment-framework/).

55 Climate Action Reserve, Options for Managing CO_2 Reversals (2010), (available at https://climateactionreserve.org/wp-content/uploads/2010/09/Options_for_Managing_CO2_Reversals_093010.pdf).

56 National Oceanic and Atmospheric Administration, The Atmosphere (2024), (available at https://www.noaa.gov/jetstream/atmosphere).

57 US EPA Office of Air and Radiation, Greenhouse Gas Equivalencies Calculator - Calculations and References (2025), (available at https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references).

58 Carbonwise, Glossary. *Carbonwise* (2023), (available at https://carbonwise.co/glossary/).

59 United Nations, "United Nations Framework Convention on Climate Change" (New York City, 1992), (available at https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf).

60 D. M. Murphy, A. R. Ravishankara, *Proc. Natl. Acad. Sci.* **115**, 13192–13197 (2018).

61 *Cal. Code Regs. tit. 17, § 95802 - Definitions* (2024; https://www.law.cornell.edu/regulations/california/17-CCR-95802).

62 ex ante. *Oxf. Engl. Dict.* (2026), (available at https://www.oed.com/dictionary/ex-post_adj).

63 ex post. *Oxf. Engl. Dict.* (2026), (available at https://www.oed.com/dictionary/ex-post_adj).

64 Verified Carbon Standard Version 5, VCS Program Definitions (2025), (available at https://verra.org/programs/verified-carbon-standard/verified-carbon-standard-version-5/).

Back cover image: Golaminnovation, Shutterstock.com

SHIFT CM

The Nature Conservancy Yale