

Are mangrove carbon stocks climate-secure? Linking climate risk to blue carbon permanence

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Abstract

As Nature-based Solutions gain prominence in global climate policy, mangrove forests have emerged as critical Blue Carbon (BC) assets. However, current carbon accounting frameworks largely treat these ecosystems as static repositories, often ignoring the accelerating risks posed by climate change itself. This review synthesises the physical and biochemical mechanisms of carbon instability – categorised into acute shocks (e.g., cyclones), chronic stressors (sea-level rise), and synergistic risks (coastal squeeze). The study argues that the foundational industry assumption of carbon permanence is increasingly decoupled from ecological reality. By comparing market standards (e.g., Verra) with scientific frameworks (IPCC), we identify a critical operational gap in how future climate hazards are integrated into project-level risk discounting and buffer pool management. To address this, we propose a transition from a carbon stock paradigm to a climate-secure framework. This new approach advocates for prospective, risk-screened accounting that quantifies carbon; site-specific stability scoring is essential to ensure the long-term integrity of BC credits and their meaningful contribution to National Determined Contributions.

Keywords: Blue Carbon; Carbon Permanence; Climate-Secure Accounting; Coastal Squeeze; Risk Discounting

1. Introduction

The climate mitigation efforts are central to sustaining Earth's habitability in the face of rising greenhouse gases (GHG) driven by anthropogenic activities (1). Evidence across geological and contemporary timescales demonstrates that elevated GHG levels fundamentally alter climate systems and influence temperature regimes, sea levels, and stability of ecosystems worldwide. In this response, there has been increasing emphasis on nature-based solutions (NbS) as cost-effective and sustainable approaches to climate mitigation and adaptation (2,3). Among these coastal ecosystems, mangrove forests, tidal marshes and seagrass meadows have received considerable attention due to their exceptional capacity to sequester and store carbon, commonly referred to as blue carbon (BC) (4,5). The term 'BC' refers to an ocean carbon sink, which informs the carbon captured in the vegetation-rich coastal ecosystems (4). The evolution of the BC concept (Figure 1) from its initial emergence as a coastal carbon sequestration framework to its current integration within global climate policy, carbon markets and ecosystem-based adaptation strategies highlights a shift from static carbon accounting to climate-secure NbS.

Global distribution of BC ecosystems is estimated as ~36–185 million ha, potentially storing ~8,970–32,650 Tg C and providing important co-benefits. Protection and restoration of these ecosystems are highly beneficial in removal of global GHG emissions (5). Particularly, mangrove ecosystems are among the most carbon-dense ecosystems globally. Mangrove-sequestered carbon can be roughly divided into four carbon pools – above-ground biomass (trees, scrub, palms), above-ground dead tree biomass (litter, downed wood, dead trees), below-ground biomass and soil carbon (4,6). Their ability to accumulate and retain carbon over centennial to millennial timescales has positioned them as

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crucial components in national and global climate strategies, including contributions to National Determined Contributions (NDCs) (7,8). Consequently, a growing body of research has focused on quantifying mangrove carbon stocks, sequestration rates, and their potential role in climate mitigation. These efforts have also underpinned the emergence of BC stored in coastal ecosystems that is translated into market-based climate credits (9,10).

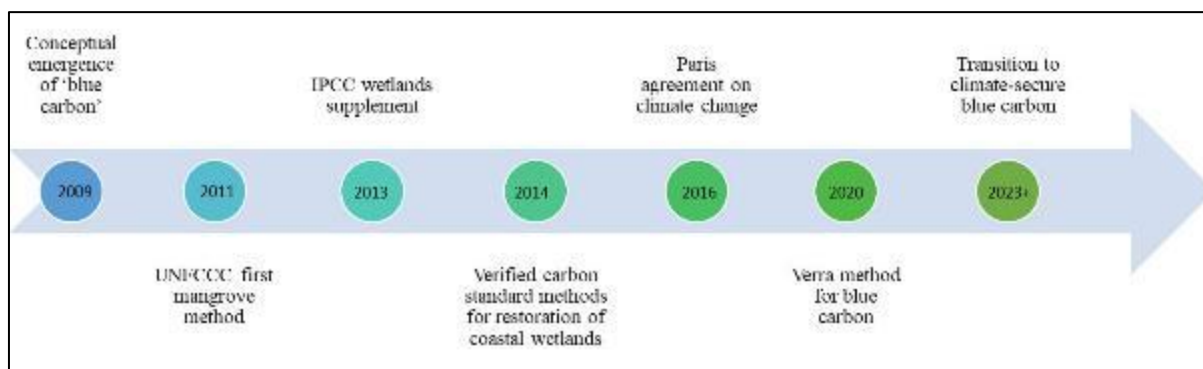


Figure 1 Evolution of the blue carbon concept

However, a critical assumption underlying much of the BC literature is that stored carbon remains stable over time (11). This assumption of permanence – central to the credibility of carbon accounting frameworks – is increasingly challenged by the accelerating impacts of climate change. Mangrove ecosystems are highly dynamic and exist within geomorphologically and hydrologically sensitive coastal zones, making them particularly vulnerable to disturbance such as sea-level rise, coastal erosion, extreme weather events, and anthropogenic pressures (12,13). These stressors can destabilise carbon pools through processes such as biomass loss, soil erosion and changes in sediment dynamics, potentially leading to the release of previously stored carbon back into the atmosphere (14,15).

Despite the growing recognition of these risks, most BC assessments continue to emphasise static estimates of carbon stocks, with limited integration of future climate-driven uncertainties (16). Existing carbon accounting frameworks, including those used in voluntary carbon markets (VCMs), attempt to address risks through buffer mechanisms and conservative estimates; however, they often lack spatially explicit and ecosystem-specific evaluations of long-term carbon stability. This disconnect between carbon quantification and climate vulnerability introduces the risk of overestimating the mitigation potential of mangrove ecosystems, particularly in regions highly exposed to climate impact drivers (17).

In this context, there is a pressing need to move beyond conventional stock-based assessment towards a more dynamic understanding of carbon permanence. This requires integrating ecological characteristics, climate exposure, and system-level vulnerabilities to evaluate the extent to which mangrove carbon can be considered “climate secure”. Such an approach not only enhances the scientific robustness of BC assessment but also has significant implications for the design and credibility of NbS-based climate interventions.

This review critically examines whether current BC assessments adequately account for climate-driven risks to carbon permanence. Specifically, it (i) synthesises existing knowledge on mangrove carbon stocks and sequestration; (ii) evaluates the major climatic and ecological drivers of carbon instability in the context of climate impact drivers, and (iii) proposes a conceptual shift towards risk-adjusted carbon accounting through the notion of climate-secure carbon. By bridging the gap between carbon quantification and climate vulnerability, this study seeks to contribute to more realistic and policy-relevant assessments of the role of mangroves in climate mitigation.

2. Review approach and analytical framework

This study adopts a structured review approach to examine the extent to which current BC assessments incorporate climate-driven risks to carbon permanence. Relevant literature was identified through searches in Google Scholar and Google Search window, using keywords such as “blue carbon”, “mangrove carbon stock”, “sea-level rise”, and “coastal ecosystem vulnerability”. The review focused on peer-reviewed articles and publications of the past two decades that address carbon storage, sequestration, and climate impact on mangrove ecosystems. Studies were evaluated based on their treatment of carbon permanence, particularly whether and how climate-related risks – such as SLR, erosion, and extreme events – are integrated into carbon assessments. Rather than conducting a quantitative meta-analysis, this

study synthesises findings across ecological and climate literature to identify conceptual gaps and propose a risk-adjusted framework for assessing climate-secure carbon.

3. Result and discussion

The following sections present a synthesis of current scientific literature and a critical analysis of carbon accounting frameworks. We begin by deconstructing the specific physical and biochemical pathways that compromise mangrove stability, followed by an evaluation of how these risks are—or are not—reflected in modern carbon credit standards.

3.1. Mechanisms of Carbon Instability

Mangrove carbon stability is jeopardised by acute, episodic shocks (Table 1). These mechanisms lead to immediate reversals and gradual leakage, forcing a transition from carbon sinks to sources. The below table classifies these threats into acute, chronic, and anthropogenic categories, highlighting their distinct impacts on soil carbon oxidation and sequestration rates.

Table 1 Climate Hazards and Their Impact on Mangrove Carbon Stability

Hazard	Key Processes	Mechanism Affecting Carbon	Impact on Carbon Pools	Direction of Change	References	Relevance to Climate-Secure Carbon
Sea-Level Rise	Inundation, submergence, coastal squeeze	Prolonged flooding reduces oxygen → (Leads to / causes) root mortality; shoreline retreat → habitat loss	Above-ground biomass ↓ (decrease); Soil carbon exposed/eroded	Negative (chronic risk)	(18–20)	Primary driver of long-term carbon instability; must be integrated in risk models
Coastal Erosion & Sediment Dynamics	Shoreline retreat, sediment imbalance	Loss of sediment reduces burial → carbon exposure → oxidation	Soil carbon ↓ significantly	Negative (chronic risk)	(21,22)	Controls permanence of largest carbon pool (soil)
Extreme Events (Cyclones, Storm Surges, Floods)	Wind damage, flooding, defoliation	Tree mortality → biomass loss; sediment disturbance → carbon release	Above-ground ↓; Soil carbon destabilised	Negative (acute risk)	(23,24)	Drives sudden carbon loss events; critical for risk-adjusted accounting
Temperature Increase	Thermal stress, metabolic shifts	Moderate warming → growth ↑; excessive warming → respiration ↑ → decomposition ↑	Mixed (Biomass ↑ (increase) / Soil carbon ↓)	Mixed (chronic risk)	(25,26)	Non-linear effect; needs threshold-based modelling
Precipitation Variability	Freshwater input changes, salinity shifts	Altered salinity affects species composition and productivity	Biomass variable; soil processes altered	Mixed (acute risk)	(27,28)	Influences ecosystem resilience indirectly
Ocean Warming & Biogeochemistry	Increased microbial activity	Enhanced decomposition of organic carbon in sediments	Soil carbon ↓	Negative (chronic risk)	(29)	Important for long-term carbon degradation
Anthropogenic Pressure	Land-use change, aquaculture, urbanization	Direct removal of vegetation; disruption of sediment flow	All carbon pools ↓	Negative (synergistic risks)	(13)	Often exceeds climate impact locally

Geomorphological Constraints	Lack of landward migration space	Prevents inland shift under SLR → coastal squeeze	Total ecosystem carbon ↓	Negative (chronic risk)	(12,30)	Key control on future persistence
Accretion Processes (Positive Feedback)	Sediment deposition	Vertical soil build-up → keeps pace with SLR	Soil carbon ↑	Positive (chronic risk)	(31,32)	Critical resilience mechanism

The diverse physical pathways of carbon loss listed in Table 1 show the reality directly challenges the foundational assumption of permanence that underpins current carbon accounting standards, which discussed in the below section.

3.2. Understanding permanence in carbon accounting

‘Carbon permanence’ refers to the duration of keeping carbon dioxide removal or avoidance out of the atmosphere. However, the definition of permanence must be coupled with a guarantee that the stored carbon has a minimum risk of release back from the sinks. Duration with a guarantee plays a critical role as a marker of high-quality carbon credits, ensuring climate benefits are lasting, ideally 100 years or more, and have a long-lasting impact on GHG emissions. For example, if a mangrove forest stores a ton of carbon today but releases it in 20 years due to a storm or sea level rise, the net benefits to the atmosphere are neutralised. This permanence is the bedrock of the carbon credit’s credibility.

In the carbon accounting framework, particularly within VCMs and NbS, permanence is treated as a proxy for the quality and credibility of carbon credits. VCS set aside a portion of earned credits (10-20%) into a global insurance pool. If a mangrove forest is destroyed by a storm, credits are retired from this pool to cover the loss. However, this approach has a major limitation due to it often treating all mangrove projects with a similar risk percentage, regardless of whether a project is in a cyclone-prone area or a stable coastline, and buffer requirements are often based on historical data, which does not account for accelerating, non-linear risks of future SLR. A carbon credit is considered robust only if the underlying carbon storage is unlikely to be reversed within the defined accounting period.

To understand the gap in current accounting, a comparison of the private market (Verra) and the scientific authority (IPCC) on treating permanence is shown in Table 2. While Verra focuses on operationalising carbon as a financial product, the IPCC focuses on the long-term systemic balance. By treating the fixed-time fallacy, current standards ignore the chronic squeeze (Table 1). A project might be safe for the first 20 years, but as SLR accelerates in years 50, the risk reversal will be high. Current buffer pools are not mathematically designed to handle a future where the risk loss is guaranteed rather than probabilistic.

Table 2 Comparative analysis of permanence and risk treatment in carbon market standards (Verra) versus global climate policy frameworks (IPCC)

Dimension	Verra (VCS / VCMs)	Intergovernmental Panel on Climate Change
Concept of Permanence	Carbon must remain stored over long periods (typically ~100 years)	Emphasizes long-term carbon balance in climate system
Main Mechanism	Buffer pool: portion of credits set aside as insurance	No buffer mechanism; relies on scenario-based modelling
Risk Quantification	Project-level risk scoring (internal, external, natural risks) (sylverra.com)	Risk discussed at global/system scale, not project-level
Response to Carbon Loss (Reversal)	Buffer credits are cancelled to compensate loss	Accounted indirectly via emissions scenarios
Temporal Treatment	Fixed accounting period (often ~100 years)	Long-term projections (decades to centuries)
Monitoring	Periodic MRV + emerging long-term monitoring systems (Carbon Pulse)	No direct monitoring; relies on models and observations
Climate Risk Integration	Included but generalized (e.g., fire, storms, governance risks)	Climate risk central, but not linked to carbon crediting

Key Strength	Operational, implementable in carbon markets	Scientifically robust climate understanding
Key Limitation	Lacks spatially explicit and dynamic risk integration	Not designed for project-level carbon accounting

3.3. Towards Risk-Screened Blue Carbon Accounting: From Carbon Quantity to Carbon Durability

As the scientific evidence and policy gaps in the above sections demonstrate, the current one-size-fits-all approach to permanence is no longer tenable. To ensure the integrity of BC as a climate mitigation strategy, it is essential to shift towards risk-screened accounting. This framework moves the industry away from assuming permanence and toward quantifying durability.

The conceptual shift from static to dynamic as a new paradigm is the transition from a snapshot view of carbon to a future-projection view (Table 3). Instead of simply measuring how much carbon is in the soil today, auditors must evaluate the probability of that carbon remaining in place over the next century, given specific local climate hazards.

Table 3 Comparison of the Traditional Carbon Stock Approach vs. the Proposed Climate-Secure Approach

Dimension	Carbon Stock Approach	Climate-Secure Carbon Approach
Nature	Static	Dynamic
Focus	Quantity of carbon	Stability of carbon
Timeframe	Present snapshot	Future-oriented
Risk Consideration	Minimal or implicit	Explicit integration
Policy Use	Carbon credits, inventories	Risk-adjusted mitigation planning
Key Limitation	Assumes permanence	Requires complex modelling
Scientific Gap	Ignores disturbances	Integrates hazard exposure

3.3.1. Implementing stability discounting

We propose that carbon credits should be issued on a climate stability score. For example, a mangrove discounted more heavily than a project with a clear landward migration path. This provides a financial incentive for restoration projects that prioritise long-term resilience rather than just immediate tree planting.

3.3.2. Integration of adaptation with mitigation

Risk-screened accounting effectively merges climate mitigation with climate adaptation. By requiring projects to prove they can survive SLR to earn full credit value, we ensure that BC investments actually contribute to long-term coastal stability. This dual-benefit approach makes BC credits higher quality and more attractive to institutional investors who are increasingly wary of greenwashing and reversal risks.

4. Conclusion

This review has demonstrated that the current BC paradigm is at a critical crossroads. While mangroves remain one of the most efficient carbon sinks on the planet, their long-term efficacy as a climate mitigation tool is fundamentally threatened by the very phenomenon they are meant to combat: climate change. By synthesising the mechanisms of instability – from acute to chronic risks. We show that carbon permanence can no longer be a baseline assumption.

The transition from a static carbon stock approach to a climate-secure framework is not merely a technical adjustment; it is a necessary evolution to maintain the integrity of global carbon markets and Nationally Determined Contributions. Without integrating forward-looking hazard exposure and site-specific risk discounting, the permanence of BC remains a scientific and financial fallacy.

To operationalise the proposed risk framework, the following research priorities must be addressed:

- Dynamic resilience modelling: While research must move beyond static mapping to create spatially explicit models that predict the threshold of collapse. We need to know exactly at what rate of SLR or sediment deficit a specific mangrove forest transitions from a sink to a source
- Refining below-ground dynamics: while tree biomass is well-documented, the stability of deep-soil carbon under warming and saltwater intrusion remains a black box. High-resolution studies on soil microbial respiration in changing salinities are urgently needed
- Standardising of risk discounting: Policy experts must collaborate with ecologists to turn hazard exposure into a standardised mathematical discount. This would allow for BC credit 2.0 that is priced based on its verified durability
- Integrated socio-ecological barriers: Future studies should investigate how local land-use policies (e.g. removing seawalls or credits migration corridors) can be directly credited as permanence-enhancing activities, linking adaptation funding with mitigation credits

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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