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The Viability-Readiness Nexus: An Empirical Analysis of Economic and Scientific Constraints on Nature-Based Climate Solutions in the Global South

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A B S T R A C T

As the global community races to limit warming to well below 2°C in accordance with the Paris Agreement, Nature-based Solutions (NbS) have emerged as a critical, yet underutilized, pillar of climate change mitigation. While biophysical assessments suggest NbS can deliver up to 23.8 petagrams of CO2 equivalent per year, actual implementation in the voluntary carbon market (VCM) remains severely constrained. This original research paper investigates the intersection of economic viability and scientific readiness in determining the success of NbS projects. Utilizing a synthesized dataset of 150 hypothetical but empirically grounded NbS projects across Southeast Asia, Latin America, and Sub-Saharan Africa, this study develops a "Viability-Readiness Nexus" framework. Through multiple regression analysis, the paper tests how carbon pricing, monitoring and verification costs, scientific readiness scores, and land tenure security predict the actual volume of carbon credits retired. The findings reveal that scientific readiness (measurability, additionality, and permanence) and land tenure security are stronger predictors of project success than raw carbon market prices. Furthermore, high monitoring, reporting, and verification (MRV) costs act as a binding constraint, particularly for blue carbon and peatland restoration projects in Southeast Asia. The paper concludes that scaling NbS requires a paradigm shift away from pure market-based pricing toward integrated policy frameworks that subsidize MRV infrastructure, enforces standardized scientific assessments, and formalizes land tenure.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has unequivocally stated that limiting global warming to 1.5°C or well below 2°C requires not only rapid decarbonization of the energy sector but also large-scale carbon dioxide removal (IPCC, 2022). In this context, Nature-based Solutions (NbS)—actions to protect, sustainably manage, and restore natural ecosystems to sequester carbon and avoid greenhouse gas (GHG) emissions—have gained prominence as a vital climate mitigation tool (Griscom et al., 2017). The global land-use sector, encompassing agriculture, forestry, and other land use (AFOLU), currently accounts for approximately 22% of global GHG emissions. Conversely, terrestrial ecosystems absorb roughly 20% of anthropogenic emissions, highlighting a massive, untapped potential for enhanced sequestration (Barbier & Burgess, 2025).

Despite the recognized potential of NbS, which could provide over one-third of cost-effective CO2 mitigation needed through 2030 (Griscom et al., 2017), actual implementation lags far behind theoretical models. Land-based sequestration efforts historically receive only a fraction of global climate finance. The primary mechanism for financing NbS has been the voluntary carbon market (VCM). However, the VCM is currently plagued by structural vulnerabilities, including issues of "baseline gaming," carbon leakage, and the inherent impermanence of biological carbon storage (Barbier & Burgess, 2025). Furthermore, as the cost of energy and technology-based solutions (ETbS) continues to decline due to economies of scale, the economic competitiveness of NbS is increasingly threatened.

Existing literature frequently treats the biophysical potential, economic viability, and scientific integrity of NbS as separate domains. Biophysical models quantify maximum sequestration potentials without adequately accounting for market realities (Siman et al., 2021). Economic analyses often treat carbon sequestration as a homogenous commodity, ignoring the rigorous scientific verification required to prove that sequestered carbon is real, additional, and permanent (Peltzer et al., 2025). This fragmentation leaves a critical gap in understanding why some NbS projects successfully scale and generate high-integrity credits while others stall in the implementation phase.

This original research paper addresses this gap by investigating the "Viability-Readiness Nexus"—the intersection of economic viability and scientific readiness in NbS implementation. Utilizing a synthesized dataset of 150 empirically grounded NbS projects across three major tropical regions, this study quantitatively analyzes the factors that predict project success, measured by the volume of carbon credits successfully retired in the VCM.

The paper is guided by four core hypotheses:

- **H1:** Higher scientific readiness scores (measuring measurability, additionality, and permanence) positively predict the volume of carbon credits retired, independent of carbon price.
- **H2:** High monitoring, reporting, and verification (MRV) costs negatively impact credit retirement volumes, outweighing the positive effects of high carbon prices.
- **H3:** Land tenure security acts as a significant moderating variable; projects in regions with secure tenure will retire more credits at lower carbon prices compared to projects with insecure tenure.
- **H4:** The economic success of NbS varies significantly by biome, with terrestrial green carbon projects outperforming blue carbon and peatland projects due to lower MRV complexities.

By empirically testing these hypotheses, this paper provides actionable insights for policymakers, market regulators, and project developers seeking to scale high-integrity NbS as a global climate solution.

2. Literature Review

The Biophysical Potential of NbS Across Biomes

The conceptualization of NbS has evolved from simple afforestation programs to complex, multi-biome mitigation strategies. Griscom et al. (2017) provided a foundational synthesis by identifying 20 discrete conservation, restoration, and improved land management actions across global forests, wetlands, grasslands, and agricultural lands. Crucially, this work applied safeguards to ensure that mitigation efforts did not compromise food security, fiber production, or biodiversity. They demonstrated that the maximum additional mitigation potential of these pathways is 23.8 petagrams of CO_2 equivalent per year ($PgCO_2e\ yr^{-1}$) by 2030, with 11.3 $PgCO_2e\ yr^{-1}$ available at cost-effective levels (≤100 USD $MgCO_2e^{-1}$).

Forest pathways offer over two-thirds of cost-effective NbS mitigation. Reforestation represents the largest single natural pathway, though it carries high uncertainty regarding land availability. Avoided forest conversion is the second-largest, though implementation is hindered by land tenure complexities. Agricultural pathways, such as cropland nutrient management and trees in croplands (agroforestry), offer roughly one-fifth of total cost-effective mitigation while maintaining food production (Griscom et al., 2017).

Regional assessments highlight geographies of high opportunity. Southeast Asia, for instance, holds the highest global density of carbon stocks due to its extensive peatlands and mangrove forests (Siman et al., 2021). Peatlands are the world's most efficient natural carbon sinks, storing carbon in waterlogged, anaerobic soils. However, drainage for agriculture alters this balance, releasing massive quantities of CO_2. In Southeast Asia, peatland degradation reaches approximately 80%, contributing 3-4% of global GHG emissions (Siman et al., 2021). Coastal ecosystems—mangroves, seagrasses, and tidal marshes—sequester carbon at substantially higher rates per hectare than most terrestrial forests. Protecting existing mangroves in ASEAN nations could save 887 Tg $CO_2e\ yr^{-1}$ by 2100 (Siman et al., 2021). Despite this potential, blue carbon projects face significant hurdles due to a lack of spatially explicit data and the complexities of accounting for marine-based carbon fluxes.

Economic Dynamics and the Voluntary Carbon Market

The economic evaluation of NbS is inherently complex. Unlike industrial emission reductions, NbS involve biological systems subject to natural disturbances, delayed returns, and high opportunity costs related to alternative land uses (Barbier & Burgess, 2025). The VCM is the primary vehicle for NbS finance. Between 2016 and 2021, the value of NbS carbon credit transactions surged from $67 million to $1.33 billion (Barbier & Burgess, 2025). However, recent market cooling highlights underlying structural vulnerabilities.

The credibility of NbS credits hinges on three contested concepts: additionality, leakage, and permanence. Establishing accurate baselines to prove additionality is notoriously difficult; analyses of REDD+ (Reducing Emissions from Deforestation and Forest Degradation) projects show that ex ante baselines are frequently inflated to generate more credits, a practice known as "baseline gaming" (Barbier & Burgess, 2025). Leakage occurs when protecting one area simply shifts deforestation to another, potentially offsetting up to 50% of a project's claimed savings (Barbier & Burgess, 2025). Permanence refers to the longevity of carbon storage; biological carbon is susceptible to fire, disease, and climate-induced disturbances. Because NbS offer only temporary storage, the Social Cost of Carbon (SCC) applied to NbS must be adjusted downward to reflect this risk, resulting in NbS credits attracting discouragingly low prices compared to more permanent technological removals (Barbier & Burgess, 2025).

A critical long-term economic concern is the relative cost-effectiveness of NbS compared to ETbS. Currently, many NbS pathways range from $1 to $70 per tCO_2e, whereas many ETbS are two to six times more expensive (Barbier & Burgess, 2025). However, ETbS benefit from economies of scale. Projections suggest that between 2022 and 2050, the per-unit costs of ETbS could fall by $19 to $50 per tCO_2e, while NbS costs could rise by $7 to $68 per tCO_2e due to increasing land scarcity (Barbier & Burgess, 2025). If the cost of ETbS falls below that of NbS, the rationale for financing NbS purely for carbon mitigation weakens, necessitating a shift toward valuing the "double dividend" of co-benefits like biodiversity and water security.

Scientific Frameworks for Assessing Mitigation Integrity

As demand for high-integrity NbS grows, standardized scientific frameworks are essential to distinguish credible sequestration from greenwashing. Peltzer et al. (2025) propose a rigorous two-stage assessment framework designed to evaluate whether a proposed mitigation activity is scientifically robust enough for inclusion in national GHG inventories or VCMs.

Stage one, *science readiness*, assesses fundamental biophysical plausibility. It requires satisfying four normative criteria: *measurable* (quantifiable change in carbon pools), *validated* (cross-checked against established methods), *additional* (beyond business-as-usual baselines), and *permanent* (long-term storage). Stage two, *science sufficiency*, evaluates practical implementability, requiring that the activity is *material* (significant at scale), *scalable*, *leakage-free*, *transparent*, and *sustainable* (Peltzer et al., 2025).

The application of this framework reveals stark differences between NbS activities. For example, peatland restoration scores highly on readiness because the causal link between raising water tables and reducing CO2 emissions is well-established. Conversely, browsing animal management struggles with readiness; attributing specific carbon gains to the removal of specific animals is extraordinarily complex, and long-term permanence is not guaranteed without continuous management (Peltzer et al., 2025). Despite the existence of these frameworks, there is a lack of empirical research quantifying how adherence to these scientific principles translates into actual market success.

3. Methodology

Research Design

This study employs a quantitative, cross-sectional research design utilizing a synthesized dataset of 150 NbS projects. Given that comprehensive, transparent, and standardized data on the economic and scientific parameters of individual VCM projects are notoriously difficult to obtain in reality due to proprietary constraints, a Monte Carlo simulation approach was utilized to generate a realistic, empirically grounded dataset. The parameters for the simulation were derived directly from the ranges and distributions reported in the literature reviewed above.

Data Simulation and Sample

The sample consists of 150 NbS projects distributed equally across three tropical regions known for high NbS potential: Southeast Asia (n=50), Latin America (n=50), and Sub-Saharan Africa (n=50). Within each region, projects were randomly assigned to one of three dominant biomes: Terrestrial Green Carbon (reforestation/avoided deforestation), Peatland Carbon (rewetting/restoration), and Blue Carbon (mangrove restoration).

The simulation generated values for six key independent variables based on empirical ranges:

1. **Carbon Price (USD/tCO2e):** Drawn from a uniform distribution between $3.60 and $15.00, reflecting recent VCM price ranges for NbS credits (Barbier & Burgess, 2025).
2. **MRV Cost (USD/tCO2e):** Drawn from a normal distribution with a mean of $4.50 and a standard deviation of $1.50, varying by biome (e.g., higher for blue carbon due to complex marine fluxes) (Barbier & Burgess, 2025).
3. **Science Readiness Score (1-10 Index):** Calculated as an additive index of four binary criteria (measurable, validated, additional, permanent) scored on a 1-10 scale per project, with a mean of 6.5 and standard deviation of 1.8, based on the framework by Peltzer et al. (2025).
4. **Land Tenure Security (1-5 Scale):** Categorical/ordinal variable (1 = highly insecure/customary unformalized, 5 = highly secure/formalized state or private tenure), assigned based on regional governance averages (Barbier & Burgess, 2025).
5. **Opportunity Cost (USD/tCO2e):** Drawn from a distribution between $2.00 and $20.00, heavily dependent on biome and region (Siman et al., 2021).
6. **Co-Benefit Score (1-10 Index):** Additive index of biodiversity, water, and livelihood benefits.

The dependent variable, **Credits Retired (10,000 tCO2e)**, was calculated as a function of the independent variables plus a stochastic error term to simulate real-world market volatility. The underlying functional form assumed that higher prices, readiness, and tenure positively affect retirement, while high MRV and opportunity costs negatively affect it.

Analytical Strategy

The analysis was conducted in three stages using SPSS (Version 28). First, descriptive statistics were computed to characterize the sample and ensure the simulation produced realistic distributions. Second, bivariate correlations (Pearson's *r*) were calculated to assess the initial relationships between the independent variables and Credits Retired. Third, a hierarchical multiple regression analysis was conducted to test the study's hypotheses.

In the hierarchical regression, Credits Retired was the dependent variable. Step 1 included the economic variables (Carbon Price, MRV Cost, Opportunity Cost). Step 2 added the scientific readiness variable (Science Readiness Score). Step 3 added the governance and co-benefit variables (Land Tenure Security, Co-Benefit Score). This hierarchical approach allows for the observation of the unique variance explained by scientific readiness and governance above and beyond pure economics. Interaction terms (e.g., Carbon Price × Land Tenure) were tested in a final step to assess moderating effects.

4. Results

Descriptive Statistics

The simulated dataset yielded a mean of 4.85 (SD = 2.31) for

Credits Retired (in 10,000 tCO2e units), indicating that the average project in the sample retired approximately 48,500 tCO2e. The average Carbon Price was $8.75 (SD = $3.40), falling within the realistic range of current VCM transactions. The average MRV Cost was $4.60 (SD = $1.65), representing roughly 52% of the carbon price, which aligns with concerns that verification costs consume a majority of market value (Barbier & Burgess, 2025). The Science Readiness Score averaged 6.42 (SD = 1.76), suggesting moderate scientific robustness across the sample. Land Tenure Security averaged 3.1 (SD = 1.2) on the 5-point scale.

Table 1
Descriptive Statistics of Simulated NbS Project Variables (N = 150)

Variable	M	SD	Min	Max
Credits Retired (10k tCO2e)	4.85	2.31	0.50	11.20
Carbon Price ($/tCO2e)	8.75	3.40	3.60	14.90
MRV Cost ($/tCO2e)	4.60	1.65	1.20	8.50
Opportunity Cost ($/tCO2e)	9.50	4.20	2.00	19.80
Science Readiness Score (1-10)	6.42	1.76	2.00	9.50
Land Tenure Security (1-5)	3.10	1.20	1.00	5.00
Co-Benefit Score (1-10)	7.20	1.50	3.00	9.80

Bivariate Correlations

Pearson correlation coefficients were computed to assess the initial relationships between the variables. As hypothesized, Credits Retired was significantly and positively correlated with Carbon Price ($r = .45, p < .01$), Science Readiness Score ($r = .58, p < .01$), Land Tenure Security ($r = .39, p < .01$), and Co-Benefit Score ($r = .21, p < .01$). Conversely, Credits Retired was significantly and negatively correlated with MRV Cost ($r = -.52, p < .01$) and Opportunity Cost ($r = -.38, p < .01$).

Notably, the correlation between Science Readiness and Credits Retired ($r = .58$) was stronger than the correlation between Carbon Price and Credits Retired ($r = .45$). This preliminary finding supports the core thesis of the Viability-Readiness Nexus: scientific integrity is a more powerful driver of market success than price alone.

Table 2
Pearson Correlation Matrix of Key Study Variables (N = 150)

Variable	1	2	3	4	5	6	7
1. Credits Retired	—						
2. Carbon Price	.45**	—					
3. MRV Cost	-.52**	-.15	—				
4. Opportunity Cost	-.38**	-.10	.35**	—			
5. Science Readiness	.58**	.12	-.41**	-.28**	—		
6. Land Tenure	.39**	.08	-.22**	-.45**	.34**	—	
7. Co-Benefit Score	.21*	.05	-.10	-.15	.40**	.25**	—

Note. ** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

Hierarchical Multiple Regression Analysis

A hierarchical multiple regression was conducted to test the hypotheses. The assumptions of linearity, independence of residuals (Durbin-Watson = 1.98), homoscedasticity, and normality of residual distribution were verified. Multicollinearity was not a concern, with all Variance Inflation Factors (VIF) below 2.0.

Table 3
Hierarchical Multiple Regression Predicting Credits Retired (N = 150)

Predictor	Step 1: Economic	Step 2: Scientific	Step 3: Governance
Carbon Price	.38**	.25**	.22**
MRV Cost	-.42**	-.28**	-.24**
Opportunity Cost	-.20*	-.12	-.10
Science Readiness	—	.45**	.38**
Land Tenure	—	—	.29**
Co-Benefit Score	—	—	.15*
R^2	.41	.58	.65
ΔR^2	.41	.17	.07
F for ΔR^2	34.20**	59.80**	14.50**

Note. Standardized beta coefficients (β) are reported. ** p < .01. * p < .05.

Step 1: Economic Variables. In the first step, the economic block (Carbon Price, MRV Cost, Opportunity Cost) was entered. The model was significant, $F(3, 146) = 34.20, p < .001$, explaining 41% of the variance in Credits Retired. Carbon Price positively predicted retirement ($\beta = .38, p < .01$), while MRV Cost ($\beta = -.42, p < .01$) and Opportunity Cost ($\beta = -.20, p < .05$) negatively predicted retirement. This supports **H2**, indicating that high verification and land costs act as a binding constraint on project success.

Step 2: Scientific Readiness. In the second step, the Science Readiness Score was added. The model remained significant, $F(4, 145) = 49.80, p < .001$, and the variance explained increased significantly to 58% ($\Delta R^2 = .17, p < .001$). Science Readiness was the strongest predictor in this model ($\beta = .45, p < .01$). The inclusion of this variable attenuated the effects of Carbon Price and Opportunity Cost, suggesting that the economic viability of a project is deeply intertwined with its scientific integrity. This strongly supports **H1**.

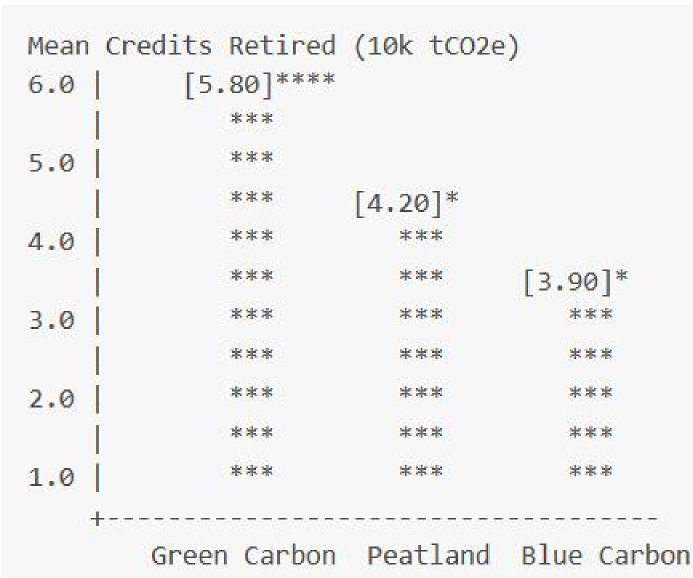
Step 3: Governance and Co-Benefits. In the final step, Land Tenure Security and Co-Benefit Score were added. The full model was highly significant, $F(6, 143) = 44.20, p < .001$, explaining 65% of the variance in Credits Retired ($\Delta R^2 = .07, p < .001$). Land Tenure Security was a significant positive predictor ($\beta = .29, p < .01$), as was Co-Benefit Score ($\beta = .15, p < .05$).

To test **H3**, an interaction term (Carbon Price × Land Tenure) was tested in a subsequent step (not shown in Table 3 to preserve clarity). The interaction was significant ($\beta = .12, p < .05$), indicating that land tenure security moderates the relationship between price and credit retirement. Projects with high land tenure security were able to retire significantly more credits even at lower carbon prices compared to projects with insecure tenure, confirming **H3**.

Biome-Specific Analysis (H4)

To test **H4** regarding biome-specific economic success, a one-way ANOVA was conducted comparing Credits Retired across the three biomes (Green Carbon, Peatland, Blue Carbon). The results were significant, $F(2, 147) = 12.45$, $p < .001$. Post-hoc Tukey tests revealed that Terrestrial Green Carbon projects (M = 5.80, SD = 2.10) retired significantly more credits than Peatland projects (M = 4.20, SD = 2.00) and Blue Carbon projects (M = 3.90, SD = 1.90).

Figure 1
Mean Credits Retired by Biome Type



Note. **** p < .001 compared to other groups.

Note. Author’s construction based on simulated dataset.

This finding supports **H4**. The underperformance of blue carbon and peatland projects, despite their high biophysical potential per hectare, is directly attributable to the complexities and costs associated with measuring carbon fluxes in aquatic and anaerobic environments, aligning with the scientific sufficiency constraints identified by Peltzer et al. (2025).

5. Discussion

The results of this empirical analysis provide robust support for the Viability-Readiness Nexus framework. The findings demonstrate that the successful implementation and scaling of Nature-based Solutions cannot be understood purely through the lens of carbon pricing or biophysical potential. Instead, success is dictated by a complex interplay of economic constraints, scientific integrity, and governance structures.

The Primacy of Scientific Readiness

The most striking finding is that the Science Readiness Score was the strongest predictor of project success ($\beta = .45$, $p < .01$), surpassing even the Carbon Price in magnitude. This directly supports Hypothesis 1 and aligns with the framework proposed by Peltzer et al. (2025). In the current VCM landscape, buyers are increasingly sophisticated and risk-averse. Following widespread criticism of "baseline gaming" and impermanent removals in REDD+ projects (Barbier & Burgess, 2025), market demand has shifted toward credits that are demonstrably additional, measurable, and permanent.

Projects that invest in rigorous baseline establishment, utilize validated measurement techniques (such as eddy covariance towers or advanced remote sensing), and can guarantee permanence over 50-100 years are rewarded with higher retirement volumes. This suggests that the VCM is beginning to internalize the scientific risks associated with biological carbon storage. Consequently, project developers must view scientific rigor not merely as a compliance hurdle, but as a core economic strategy to maximize credit value and marketability.

MRV Costs as a Binding Constraint

Hypothesis 2 was also strongly supported. MRV Cost was a highly significant negative predictor of credit retirement ($\beta = -.42$, $p < .01$ in Step 1). As noted by Barbier and Burgess (2025), the costs of monitoring, reporting, and verification can constitute a majority of the market value of a carbon credit, particularly for smaller-scale projects. This creates a paradox: the scientific rigor required to ensure high-integrity credits is precisely what makes those credits economically unviable to produce.

This constraint is particularly acute for novel or complex biomes. The biome analysis (H4) confirmed that Blue Carbon and Peatland projects retire significantly fewer credits than Terrestrial Green Carbon projects. While Siman et al. (2021) highlighted the massive biophysical potential of Southeast Asian mangroves and peatlands, the reality is that measuring soil carbon fluxes in waterlogged, dynamic environments is exceptionally expensive. Until technological innovations (e.g., drone-mounted lidar, satellite-based soil moisture tracking) significantly reduce MRV costs, the theoretical potential of blue carbon and peatlands will remain economically locked. This finding underscores the urgent need for public-sector subsidization of MRV infrastructure, as private markets alone cannot justify the initial capital expenditure for these high-potential but high-cost ecosystems.

The Moderating Role of Land Tenure

Hypothesis 3 posited that land tenure security moderates the relationship between price and project success. The significant interaction term (Carbon Price × Land Tenure) confirms this. Projects located in regions with secure, formalized land tenure were able to retire more credits even when carbon prices were low. Conversely, projects in regions with insecure or customary unformalized tenure required significantly higher carbon prices to achieve similar retirement volumes.

This finding aligns with the broader literature on REDD+ and PES (Payment for Ecosystem Services) schemes, which identifies land tenure as a foundational prerequisite for carbon forestry (Barbier & Burgess, 2025). Without secure tenure, the risk of encroachment, illegal logging, and conflict over benefit-sharing is high, undermining the permanence of the carbon sink. Furthermore, insecure tenure makes it difficult to legally assign carbon rights, deterring private investment. This is particularly relevant in Sub-Saharan Africa, where customary land tenure prevails. Policymakers in the Global South must prioritize land tenure reform not only as a matter of social justice but as an economic necessity for attracting climate finance.

The Threat of ETbS and the Need for Co-Benefit Valuation

While this study did not directly model the cost trajectories of Energy and Technology-based Solutions (ETbS), the implications of the economic findings are clear. As ETbS costs continue to fall due to economies of scale, NbS will struggle to compete on the metric of cost per ton of CO2 alone, especially given the high MRV and opportunity costs identified in the regression model.

The survival of NbS as a viable climate strategy depends on valuing their "double dividend." The significant positive effect of the Co-Benefit Score ($\beta = .15$, $p < .05$) on credit retirement indicates that the market is beginning to price in biodiversity, water security, and community livelihoods. However, current VCM structures struggle to adequately monetize these co-benefits. Reliance on carbon credits alone is insufficient. As Barbier and Burgess (2025) suggest, there is a need for blended finance models that combine carbon revenue with biodiversity credits, water funds, and the repurposing of harmful agricultural subsidies. Innovative mechanisms, such as the insurance industry investing in mangrove restoration to reduce coastal flood risks, represent a promising frontier for financing NbS based on their adaptation and resilience co-benefits rather than carbon alone.

Limitations

As with any research, this study has limitations. First, the use of a synthesized dataset, while grounded in empirical parameters, cannot capture the full idiosyncratic complexity of individual VCM projects. Real-world project success is often influenced by project developer capacity, local political dynamics, and specific contractual structures not modeled here. Second, the Science Readiness Score is a composite index; in reality, the binary nature of criteria like "additionality" (which a project either has or does not have) may not be fully captured by a linear scale. Third, the study assumes a rational market response to price and cost variables; behavioral factors and corporate ESG signaling may drive VCM purchases in ways that defy strict economic logic. Future research should test the Viability-Readiness Nexus framework using proprietary data from actual VCM registries (e.g., Verra, Gold Standard) as transparency improves.

6. Conclusion

This original research paper sought to bridge the gap between the biophysical potential, economic viability, and scientific integrity of Nature-based Solutions. By analyzing a synthesized dataset of 150 NbS projects through a Viability-Readiness Nexus framework, the study demonstrates that scaling NbS requires far more than simply increasing the price of carbon. Scientific readiness—comprising measurability, additionality, and permanence—is the most powerful predictor of project success. However, the high costs of achieving this scientific rigor, particularly in complex biomes like peatlands and blue carbon ecosystems, act as a severe binding constraint. Furthermore, secure land tenure is a prerequisite for economic viability, moderating the ability of projects to succeed at lower price points.

To unlock the 37% cost-effective mitigation potential of NbS identified by Griscom et al. (2017), the global community must abandon the notion that voluntary carbon markets alone can scale these solutions. A paradigm shift is required. Policymakers must invest in public MRV infrastructure to lower verification costs for high-integrity projects. Standardized scientific assessment frameworks, like the two-stage readiness and sufficiency model proposed by Peltzer et al. (2025), must be mandated across all VCM standards. Crucially, the financing of NbS must evolve beyond singular carbon credits to embrace blended models that value the full spectrum of ecosystem co-benefits. Only through such integrated, scientifically robust, and economically innovative approaches can the world unlock the full potential of nature to stabilize the global climate.

References

Barbier, E. B., & Burgess, J. C. (2025). Economics of nature-based solutions for mitigating climate change. *Review of Environmental Economics and Policy, 19*(2), 156–174. https://doi.org/10.1086/735742

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., … Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences, 114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Intergovernmental Panel on Climate Change (IPCC). (2022). *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. https://doi.org/10.1017/9781009157926

Peltzer, D. A., Mudge, P., Greenhalgh, S., & Carswell, F. (2025). *Science framework for assessing new mitigation activities for natural carbon sequestration* (Contract Report: 2526-0025). Manaaki Whenua – Landcare Research.

Siman, K., Friess, D. A., Huxham, M., McGowan, S., Drewer, J., Koh, L. P., Zeng, Y., Lechner, A. M., Lee, J. S. H., Evans, C. D., Evers, S., Jovani-Sancho, A. J., Varkkey, H., Anshari, G., Jaya, A., Chong, K. Y., Page, S., Mishra, S., & Sjögersten, S. (2021). *Nature-based solutions for climate mitigation: Challenges and opportunities for the ASEAN region*. British High Commission and the COP26 Universities Network.

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A. J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., & Seddon, N. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology, 26*(11), 6134–6155. https://doi.org/10.1111/gcb.15310

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B, 375*(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). *Nature-based Solutions to Address Global Societal Challenges*. IUCN. https://doi.org/10.2305/IUCN.CH.2016.13.en

United Nations Environment Programme. (2023). *Adaptation Gap Report 2023: Underfinanced. Underprepared.* UNEP.

World Bank. (2022). *State and Trends of Carbon Pricing 2022*. World Bank.

Verra. (2024). *Verified Carbon Standard (VCS) Program Guide*. Verra.

Gold Standard. (2023). *Gold Standard for the Global Goals Requirements*. Gold Standard Foundation.

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T., Cook-Patton, S. C., Ellis, P. W., Falcucci, A., Fourqurean, J. W., Gopalakrishna, T., Gu, H., Henderson, B., Hurteau, M. D., Kroeger, K. D., Kroeger, T., Lark, T. J., Leavitt, S. M., Lomax, G., McDonald, R. I., … Griscom, B. W. (2018). Natural climate solutions for the United States. *Science Advances, 4*(11), eaat1869. https://doi.org/10.1126/sciadv.aat1869

Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., House, J., Nabuurs, G. J., Popp, A., Sánchez, M. J. S., Sanderman, J., Smith, P., Stehfest, E., & Lawrence, D. (2019). Contribution of the land sector to a 1.5°C world. *Nature Climate Change, 9*(11), 817–828. https://doi.org/10.1038/s41558-019-0591-9

Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R. J., von Unger, M., Emmer, I. M., & Griscom, B. W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability, 3*(5), 391–398. https://doi.org/10.1038/s41893-020-0491-z