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Review Article

Global Forest Carbon Project Evaluation System

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Abstract: In response to growing concerns over the reliability of nature-based solutions, this research scrutinizes the systems governing forest carbon projects at national, regional, and project levels. The findings demonstrate significant heterogeneity in evaluation criteria, highlighting a critical misalignment between policy mandates and field-level execution. Significant deficits in transparency and quantification accuracy are identified as primary drivers of over-crediting risks, which fundamentally undermine global climate targets. To rectify these failings, the study proposes an integrated assessment architecture that combines high-resolution technological verification with inclusive social safeguards, providing a blueprint for high-integrity carbon markets.

Keywords: Forest carbon, Evaluation system, Project scale, Protocols, Standards.

1. Introduction

Forests play a central role in global efforts to mitigate climate change due to their ability to absorb and store CO_2 from the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) report highlights that limiting global temperature rise to 1.5-2°C, as outlined in the Paris Agreement, will not be achievable without significant reductions in emissions from deforestation and forest degradation, alongside enhanced CO_2 removal from terrestrial ecosystems [1, 2]. Studies estimate the potential for greenhouse gas (GHG) emission reductions from forests and other natural ecosystems to range from 100 to 1,000 Gt CO_2-eq by the end of the century, with the cost-effective and resource-feasible range falling within the lower 20% of this spectrum [3, 4]. In this context, forest carbon credit (FCC) systems are emerging as an important tool for financing nature-based climate solutions and promoting sustainable land use.

Forest carbon projects play a pivotal role in global emission reduction strategies, particularly through voluntary and mandatory carbon markets. However, approximately 40% of global credits and 47% of credits in North America on the voluntary market originate from the forestry

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sector, and despite reaching a value of USD 2 billion in 2022, this market is currently declining due to concerns over the transparency and reliability of credits. Many projects fail to deliver the climate outcomes they promised, reflecting shortcomings in the current certification systems [2, 5, 6]. These markets operate based on protocols or standards that assess carbon levels, defining eligibility criteria for projects, monitoring methods, and calculations for CO_2 absorption or emission reductions. These protocols aim to ensure that credits issued are additional, permanent, and accurately quantified, thus maintaining the environmental integrity of both voluntary and regulated carbon markets [7, 8]. However, recent empirical studies have highlighted significant weaknesses in these systems, including over-crediting, unreasonable baseline construction, and the creation of perverse incentives that may undermine market credibility [9-12].

One of the most widely adopted approaches is Improved Forest Management (IFM), which is considered to have the potential to absorb 0.2–2.1 Gt CO_2e per year globally without harming the ecological or economic benefits of forests [12, 13]. However, technical inconsistence in risk assessment and leakage control, alongside standard fragmentation, obscure protocol selection and erode the transparency of the IMF market [2, 7].

As FCC become integral to global climate policy, systematically evaluating forest carbon frameworks is imperative. These systems serve as the primary determinants of credit integrity, implementation efficacy, and market participation. Therefore, the aim of this study is to provide an overview and comparative analysis of forest carbon project evaluation systems at various scales (national, regional, and project-specific) in order to: i) Clarify the differences in objectives and evaluation criteria between systems; ii) Analyze the enabling conditions, quantitative methods, and carbon monitoring used; and iii) Compare the transparency, scientific reliability, and effectiveness of different systems. In doing so, the study contributes to identifying gaps in system design, proposing solutions to harmonize quantitative methods, and providing an academic and practical foundation to enhance the credibility and effectiveness of FCC systems on a global scale [8, 12].

2. Methodology

This study employs a multi-tiered analytical framework to evaluate FCC systems across three implementation scales: national, regional, and project-specific. The comparative analysis is structured around standardized environmental integrity criteria, including additionality, baseline determination, leakage, permanence, monitoring, reporting, and verification (MRV) protocols, alongside transparency and economic efficiency. This stratified approach facilitates the identification of cross-scalar interactions and systemic gaps, supporting the design of flexible and effective carbon policies [12, 14-16].

To ensure a comprehensive and replicable synthesis, a systematic literature review was conducted. The primary data acquisition involved a structured search across three major academic databases: Web of Science, Scopus, and Google Scholar. The search strategy utilized a combination of Boolean operators and specialized keywords, including: *("forest carbon" OR "REDD+") AND ("evaluation system" OR "protocols" OR "standards") AND ("additionality" OR "leakage" OR "permanence" OR "MRV")*. This was supplemented by a targeted gray literature search of official registries and technical repositories from major carbon standard bodies, such as Verra (Verified Carbon Standard -VCS), the Gold Standard (GS), Climate Action Reserve (CAR), and the American Carbon Registry (ACR), as well as national policy frameworks. The temporal scope was set from 2000 to 2025 to capture the evolution from early Kyoto Protocol mechanisms to the current Article 6 landscape.

Documents and protocols were filtered based on rigorous eligibility criteria to maintain scientific integrity. Inclusion criteria required

that the selected sources: i) provide explicit, quantifiable methodologies for carbon stock assessment; ii) define clear MRV procedures; and iii) contain empirical data or critical analyses regarding the implementation of additionality and leakage safeguards. Exclusion criteria were applied to: i) non-English publications without official translations; ii) studies focusing solely on technical remote sensing algorithms without reference to policy or evaluation frameworks; and iii) anecdotal reports lacking peer-reviewed or institutional validation.

The final evidentiary base, comprising core scientific papers and institutional protocols, is summarized in Appendix 1. Furthermore, the study integrates representative case study analyses at each implementation level. These cases serve to validate the theoretical criteria against real-world enforcement contexts, ensuring the comparative analysis remains grounded in practical application.

3. Results and Discussion

3.1. Overview of Forest Carbon Project

3.1.1. Classifications of Forest Carbon Projects

The credits generated by forest carbon projects are primarily classified into the following key categories:

REDD+ (Reducing Emissions from Deforestation, Forest Degradation, and "Plus" activities) projects are a global mechanism developed under the framework of the United Nations Framework Convention on Climate Change (UNFCCC) to provide financial incentives for developing countries to protect and sustainably manage their forests [17, 18]. Originally focusing on reducing emissions from deforestation and forest degradation, the REDD+ mechanism has expanded to include the conservation of forest carbon stocks, sustainable forest management, and the enhancement of forest carbon stocks through reforestation and forest restoration [18]. REDD+ programs are implemented in a three-phase process: i) Development of national strategies, policies, and capacity; ii) Pilot and implementation activities, alongside technology transfer; and iii) Implementation of results-based actions, with MRV mechanisms, serving as the basis for results-based payments [17]. To date, over 60 developing countries have participated in REDD+, viewing it as a key forestry tool for addressing climate change. In addition to environmental factors, REDD+ requires that social and environmental safeguards be designed and adhered to, through national forest monitoring systems and transparent reporting of safeguards criteria [17].

Afforestation/Reforestation (AR) projects refer to activities or actions aimed at planting new forests or replanting forests to achieve carbon removal from human-induced greenhouse gases through carbon sinks, whether as independent projects or as part of broader climate and land use programs [2, 19]. Trees are planted on one of the following land types: i) land that has never been forested before; ii) land that has been deforested for at least 10 years; or iii) areas that need replanting to restore ecological integrity. However, forests must be defined as a minimum area of 0.05–1.0 hectares, with canopy cover (or equivalent planting density) exceeding 10–30%, and tree species capable of reaching a minimum height of 2–5 meters at maturity in situ [19]. This can include: i) closed canopy forests, where trees have multiple layers and undergrowth covers most of the ground, or sparse forests with multiple canopy layers and undergrowth; ii) young or planted forests that have not yet reached canopy or height standards; (iii) areas of temporarily lost forest due to human or natural disturbances but with potential for natural regeneration.

Improved Forest Management (IFM) projects are forest management activities aimed at increasing forest carbon stocks and/or reducing GHG emissions from forestry activities compared to business-as-usual practices [2, 20]. IFM projects may include extending harvesting cycles, applying reduced-impact logging techniques, forest fire and pest management, or

converting part of the forest area to conservation [21]. Depending on the measures applied, IFM can either conserve existing carbon stocks (e.g., by reducing harvesting intensity) or increase carbon sequestration by improving forest growth conditions. Therefore, IFM can play a dual role: both reducing emissions and removing CO_2 from the atmosphere.

Avoided Conversion (AC) projects aim to prevent the planned conversion of forests into other land uses, such as agriculture or urban development [2].

Forest Ecosystem Restoration (FER) projects focus on enhancing carbon stocks and improving ecological functions on degraded forest lands.

3.1.2. Classification by Market Mechanism

Carbon markets are currently divided into two main types: Compliance Carbon Markets (CCM) and Voluntary Carbon Markets (VCM) [22–24]. CCM refers to markets where countries or emitting entities are required to trade carbon credits to meet emissions reduction obligations under regulations or international treaties, such as the Clean Development Mechanism (CDM) and Joint Implementation (JI) under the Kyoto Protocol, or systems like the EU ETS (Emissions Trading Scheme), UK ETS, and China ETS [26]. Emerging mechanisms such as CORSIA and Article 6 of the Paris Agreement (particularly Articles 6.2 and 6.4) are expected to succeed the CDM, allowing authorized credit trading between countries [24]. Due to their mandatory nature, credit prices in CCM are typically higher, and credits may be resold on the VCM.

In contrast, VCM enables individuals or organizations to voluntarily purchase carbon credits to offset emissions or achieve sustainable development goals, without legal obligations or binding commitments [23-25]. VCM is supported by standards such as the VCS, GS, ART/TREES, Joint Crediting Mechanism (JCM), and Plan Vivo, with credit issuance and trading monitored by independent organizations rather than governments [22, 26]. As VCM is not legally binding, credit prices are generally lower than in CCM, and credits from the VCM are typically not included in national commitments unless authorized under the terms of the Paris Agreement [23].

3.1.3. Classification by Project Scale

i) Classification of forest carbon projects by scale

The classification of forest carbon projects by scale is a critical factor that influences the methodology, financial registration, verification processes, and market access. Small-scale projects typically incur lower management costs and foster greater community involvement, but generate fewer credits. In contrast, large-scale projects produce more credits but require significant technical expertise and financial resources. Each standard, such as CDM, VCS, GS, ART-TREES, etc., has its own criteria for scale classification, which impacts credit recognition, market price, and access to compliance or voluntary markets. Under the CDM, AR projects are classified into three categories: micro ($\leq$ 20,000 tCO_2e/year), small ($\leq$ 80,000 tCO_2e/year), and large (>80,000 tCO_2e/year). The GS classification is similar: micro ($\leq$ 16,000 tCO_2e/year and $\leq$ 500 ha), small ($\leq$ 16,000 tCO_2e/year), and large (>16,000 tCO_2e/year), with a preference for small projects due to their community and household benefits [27]. Verra offers various programs: VCS applies to AR, IFM, and REDD+ projects [28]; Jurisdictional and Nested REDD+ (JNR) does not distinguish scale for REDD+ projects; CCB targets projects by farmers or communities without scale differentiation; while SD VISta incorporates scale-dependent criteria for projects delivering sustainable development co-benefits [29].

ii) Classification by implementation level

Beyond project scale, stratifying forest carbon initiatives by implementation level (national, jurisdictional, and project-based) is essential for ensuring policy alignment, financial transparency, and operational efficacy [30-32]. At the national level, a prime example is national REDD+ programs, where national mechanisms require inventorying emissions and forest carbon stocks according to the UNFCCC reporting

framework, creating a comprehensive MRV foundation. This model helps reduce baseline discrepancies and enhances national-level assessment capabilities [30, 33]. At the jurisdictional level, regional REDD+ approaches help minimize leakage by implementing coordinated control at larger administrative regions. Jurisdictional programs are often more effective in addressing the drivers of deforestation and creating a better policy monitoring framework compared to smaller project-level efforts [34]. At the project level, initiatives like IFM are typically implemented independently at the local level, increasing adaptability and community participation, but may face risks such as overestimation and high leakage due to insufficiently conservative baselines [12]. This classification approach integrates scale with standardized criteria to clarify the advantages and drawbacks at each level, ultimately guiding the design of effective and sustainable carbon credit policies.

3.2. Protocols and Standards for Evaluating Forest Carbon Projects

3.2.1. Additionality

Additionality is the cornerstone of environmental integrity, requiring that emission reductions occur solely as a direct result of carbon finance rather than business-as-usual activities [35]. According to the ICVCM [35], projects must demonstrate additionality through one of three methods: i) investment analysis combined with a baseline assessment, ii) barrier analysis, or iii) a standardized approach. Alternative methodologies necessitate transparent, detailed justification, while credit renewals mandate periodic additionality reassessments to ensure ongoing integrity.

The ICVCM's evaluation framework comprises nine (9) criteria, with common criteria including: (1) the project must demonstrate compliance with current legal requirements and undergo independent verification (Criterion 1); (2) there must be verifiable evidence of intent to participate in the carbon market prior to project implementation (Criterion 2); and (3) the project must select one of three methods to prove additionality, including: i) investment analysis combined with baseline assessment (Criteria 4 and 6), ii) barrier analysis combined with baseline assessment (Criteria 5 and 6), or iii) the application of a standardized approach (Criterion 7). For jurisdictional REDD+ projects, additional criteria (Criteria 8 and 9) require a specific action plan and evidence that the financial incentives from credits are a decisive factor for implementation.

3.2.2. Accountability

The reduction or removal of GHG emissions from mitigation activities must be quantified with certainty, based on precautionary, comprehensive, and scientifically reliable methods [35]. This means that the amount of GHG reduction must be accurately measured, avoiding overstatements, managing uncertainties effectively, following transparent verification processes, and ensuring that emission reductions are independently verified after implementation.

Measurement methods must align with international standards such as CORSIA and meet technical requirements for: emission scope and boundaries, establishment of a reasonable baseline, assessment and mitigation of emission leakage, ensuring the causal link between emission reduction impacts, and establishing a continuous monitoring system. In the future, these standards will be periodically updated, with a trend toward standardization and stricter measurement criteria to enhance the accuracy and environmental efficacy of the credits. Notably, ex-ante credits will no longer be recognized as valid for accounting towards emissions reductions or removals.

3.2.3. Permanence

Permanence reflects the ability to maintain reduced or removed GHGs from the atmosphere over the long term, thus preventing reversals, such as through forest fires, logging, or natural disasters that could lead to the re-release of sequestered carbon [28, 35].

Ensuring emission reduction permanence requires robust reversal safeguards. Certain types of projects, such as ecosystem conservation, wetland restoration, or soil carbon sequestration, are required to commit to a minimum of 40 years of monitoring and buffer reserve commitments. Specifically, for JNR projects, ICVCM applies a separate mechanism, which will continue to be refined in future versions [35].

3.2.4. Leakage

Leakage refers to an increase in emissions or a reduction in carbon stocks that occurs outside the project boundaries but can be directly attributed to the project, particularly in afforestation or reforestation projects [28, 35]. Verra [28] and ICVCM [35] have provided several examples of leakage types, as outlined in Table 1. Consequently, leakage must be accounted for and controlled, which involves monitoring emissions resulting from leakage in neighboring areas and offsetting these emissions at the time and location where they occur.

3.2.5. Co-benefits (Economic, Social, Environmental)

Co-benefits are positive outcomes that extend beyond the primary goal of emissions reduction, including improvements in health, energy security, employment, and sustainable development [36,37]. Most GHG mitigation policies aim at achieving social and economic objectives. Carbon credit projects, such as the CDM, often provide simultaneous economic benefits (e.g., job creation, poverty reduction), social benefits (e.g., improved health, empowerment), and environmental benefits (e.g., pollution reduction, resource conservation). To optimize co-benefits, it is essential to identify development needs related to climate change, strengthen cooperation mechanisms, and develop practical guidelines and quantitative/qualitative assessment tools [38].

Table 1. Types of leakage

Leakage type	Mechanism	Representative example	Recommended quantification
Activity - shifting	Displacement of emissive activities to unsupervised areas.	Relocation of subsistence farming due to ARR implementation.	Land-use mapping, satellite monitoring, field surveys of adjacent areas.
Ecological leakage	Indirect emissions occurring in ecologically connected areas (e.g., hydrology, climate).	CO_2 emissions from soil due to flooding when water levels are lowered.	Hydrological modeling, GHG measurement in ecologically linked areas, field survey data.
Market leakage	Supply/demand shifts incentivizing production elsewhere.	An IFM project may cause market leakage (e.g., logging activities move to other areas).	Market analysis, supply-demand models, supply chain data, industry statistics.
Upstream/ Downstream Emissions	Emissions occurring in the value chain related to mitigation activities, either before or after mitigation efforts.	CH_4 emissions from natural gas extraction during production of natural gas used as fuel or feedstock in mitigation activities.	Life cycle assessment (LCA), standard emission factors (IPCC, GREET), supply chain data.

(Source: [28, 35]).

3.2.6 Equity and Indigenous Peoples' Rights

Indigenous Peoples and Local Communities (IPLCs) involved in carbon credit projects play key roles as landowners and forest managers, especially in regions with high carbon stocks and intact ecosystems. Indigenous peoples manage approximately 36% of the world's intact forests and were estimated to oversee 17% of global

carbon stocks (nearly 300 billion tons) across 64 countries as of 2018, encompassing all major global forest areas [25]. IPLCs can participate as landowners, partners, or beneficiaries, but there are risks of exclusion from decision-making processes if transparent consultation mechanisms and recognition of rights are lacking.

Ensuring equitable and effective participation of IPLCs is a prerequisite for the long-term success of carbon credit projects. Adopting the "Free, Prior, and Informed Consent" (FPIC) process, clear and transparent grievance mechanisms, and specific, transparent benefit-sharing systems are mandatory [35]. Additionally, projects must avoid negative impacts on the territories, livelihoods, and cultural heritage of communities, and respect traditional rights, particularly for uncontacted groups.

According to ICVCM [35], project documentation must clearly outline the benefit-sharing plan, FPIC process, and safeguards for cultural and social rights. These elements should be evaluated, validated, and publicly disclosed, ensuring alignment with national laws and international standards.

3.3. Overview of FCC Project Evaluation Systems at National, Regional, and Project Scales

Appendix 1 summarizes a selection of FCC projects representing evaluation systems at various scales (national, regional, and project levels), demonstrating the diversity in approaches, objectives, and evaluation criteria. These differences reflect varying policy interventions, technical requirements, and utilization goals across different levels.

Objectives and evaluation criteria of FCC systems at different scales: FCC evaluation systems at national, regional, and project scales are designed with distinct objectives and criteria, reflecting different levels of policy intervention and carbon credit utilization. At the national level, systems like New Zealand's Emissions Trading Scheme (NZ ETS) and the ART-TREES REDD+ program focus on managing national emissions, aligning with commitments under the Paris Agreement. Consequently, evaluation criteria are comprehensive, encompassing ARR and IFM to ensure balance within mandatory emission systems [39]. In contrast, regional systems like the Regional Greenhouse Gas Initiative (RGGI) in the United States coordinate between multiple states and allow for very limited forest credit allocations (under 0.01% of the cap), primarily aiming to ensure additionality and prevent reversal risks, reflecting a cautious political and scientific stance [40]. At the project scale, systems such as Australia's Emissions Reduction Fund (ERF), California's CARB, and voluntary protocols like ACR and CAR focus primarily on generating measurable, verifiable, and tradable carbon credits, incentivizing private investment in forest protection and restoration. Evaluation criteria at this scale emphasize additionality, using barriers such as legal, financial, or practical comparisons [11, 41].

Eligibility conditions, quantification methods, and MRV systems: The differences in eligibility conditions and quantification methods across scales are evident in the standardization levels, technical complexity, and MRV mechanisms. At the national scale, systems like New Zealand's ETS classify forests based on the 1989 cutoff year to determine project validity, employing average inventory or stock change accounting methods to simplify carbon measurement processes. These systems often require periodic reporting and impose penalties if discrepancies or reversal risks arise [39]. At the regional scale, as seen in RGGI, stricter MRV requirements include performance evaluations and default leakage factors (3.6% for activity leakage and 20% for market leakage), along with a commitment to monitoring lasting up to 100 years to ensure the sustainability of issued credits [40]. Conversely, project-level systems utilize advanced technical tools like FullCAM (Australia) or CARIT (USA), combining field data, satellite imagery, and GIS to estimate carbon, though these face methodological risks due to counterfactual baselines, which are difficult to verify and

susceptible to manipulation [12, 42]. Over-crediting, especially in IFM projects in California, Australia, and voluntary programs, has been widely observed [10], while factors like carbon leakage due to market changes or activity shifts have not been adequately assessed [43].

Transparency, scientific credibility, and practical effectiveness: The levels of transparency and scientific credibility across FCC systems vary according to the scale of implementation, reflecting trade-offs between practical feasibility and technical accuracy. At the national level, systems like New Zealand's ETS and China's CCER operate with high policy transparency, but their scientific credibility is limited due to simplified quantification methods and a lack of independent verification mechanisms [39, 44]. In contrast, project-level systems like CARB (California) achieve high accuracy through detailed technical guidelines, rigorous inventory methods, and third-party monitoring, but they face challenges related to compliance costs and accessibility for small-scale stakeholders [45, 46]. In Australia, the ERF program has faced criticism for its low effectiveness in reducing actual emissions, as projects designed to prevent land-use conversion fail to demonstrate additionality [41]. Voluntary protocols such as VCS or CAR allow flexible methodologies but still face risks of unreliable credits due to poor baselines and inadequate buffer pool mechanisms to mitigate reversal events like wildfires [11]. Regional systems such as RGGI tend to strike a balance between transparency and efficiency, maintaining lifetime monitoring mechanisms while applying stringent risk adjustment factors. A commonality across all scales is the recognition of environmental and social co-benefits (e.g., biodiversity conservation, livelihood improvement). However, at the project scale, particularly in voluntary mechanisms like Plan Vivo or VCS, these co-benefits are more rigorously measured and reported, while at the national level, they are often considered non-mandatory supplementary benefits [46].

3.4. Overview of FCC Project Evaluation Systems at National, Regional, and Project Scales

3.4.1. Differences in Objectives and Evaluation Criteria Across Multi-scale Systems

The system for evaluating forest carbon projects exhibits significant diversity in terms of objectives and criteria, reflecting differences in the scale of application and policy orientation. At the national level, the primary goal is closely tied to fulfilling climate commitments under the Paris Agreement, such as integrating FCC into cap-and-trade systems to meet NDC targets [15]. In contrast, at the project or regional level, protocols such as REDD+ or IFM focus on generating tradeable credits to mobilize financial resources from the carbon market [12]. The acceptance of FCC also varies considerably: New Zealand and Australia actively use forest credits as part of their national strategies, even implementing policies to penalize deforestation [47], whereas the EU Emissions Trading System (EU ETS) completely excludes forest credits from its compliance market [7, 48]. This highlights the lack of international consensus regarding the role of forests in achieving global emission reduction targets [15].

3.4.2. Quantification Methods and MRV

The assessment of FCCs is fundamentally constrained by divergent approaches to establishing counterfactual baselines and verifying additionality, leading to significant variability in credit quality. Current protocols allow project developers to select baseline scenarios that are financially advantageous, such as those based on the highest Net Present Value (NPV) models [12], leading to the phenomenon of over-crediting [11, 12]. The assessment of additionality often relies on subjective information provided by project developers, lacking independent verification mechanisms [49]. Unrealistic assumptions, such as the complete degradation of land, have been criticized for introducing significant bias in the number of credits issued [50].

At the monitoring level, national MRV systems are typically standardized, utilizing

remote sensing technologies and verified statistical data [15]. Conversely, project-level MRV frameworks remain characterized by excessive complexity and opacity; the associated administrative burden is substantial, potentially consuming up to 42% of total project expenditures [49, 51]. This not only reduces the economic efficiency of small-scale projects but also exacerbates information asymmetry between project developers, verification bodies, and local communities [12, 49].

3.4.3. Transparency, Credibility, and Efficiency Across Systems

A concerning commonality across most systems is the lack of transparency and reliability in assessing risks and factors influencing the longevity of FCC. While many protocols incorporate buffer pools as a precautionary measure, the contribution levels often fail to accurately reflect regional risk analyses and are not updated regularly [2, 52]. Haya et al. [12] caution that numerous protocols underestimate the risk of reversals and do not integrate measures to enhance ecological resilience.

Similarly, leakage assessments continue to rely on fixed coefficients, despite evidence showing that leakage rates can vary significantly depending on the region and market conditions [2, 53]. The failure to update these assessments with field data results in substantial discrepancies in the number of credits recognized [12]. Furthermore, certain protocols overlook the actual decay cycle of harvested wood products (HWPs), thereby diminishing the accuracy of long-term carbon quantification methods [12].

3.4.4. Structural Issues and Equity

The integrity of FCM (Forest Carbon Market) is not only threatened by technical challenges but also by institutional shortcomings and social equity concerns. Many independent validation/verification bodies (VVBs) have been accused of conflicts of interest during the certification process, along with a lack of data transparency and the absence of mechanisms to address low-quality credits ("legacy credits") [2]. The existence of multiple distinct standards, without a coordinating international framework, increases transaction costs and complicates investors' ability to assess the quality of credits [7].

At the project level, social equity factors, particularly land rights, community participation, and BSM (Benefit Sharing Mechanism), are often overlooked. Numerous projects have been accused of undermining local land control or lacking proper consultation processes [54-56]. Studies indicate that without transparency and clarity regarding ownership and benefit-sharing, projects struggle to achieve long-term sustainability [49, 57]. Furthermore, high transaction costs, especially those associated with complex MRV requirements, have rendered small-scale projects economically unfeasible [49, 51, 58].

3.4.5. Trade-offs between Carbon Sequestration and Biodiversity

An increasing concern is the potential for forest carbon projects to create unintended trade-offs between carbon sequestration and biodiversity conservation. The preference for monoculture plantations or fast-growing forests to maximize carbon accumulation is often undermining ecological functions and causing the loss of natural habitats [59, 60]. Many existing protocols fail to adequately integrate ecological indicators, such as soil quality, habitat connectivity, or ecosystem restoration, leading to long-term ecological risks [49, 57].

Overall, the debates surrounding FCC systems reflect a lack of consistency across governance levels and weaknesses in technical design. The differences in objectives, carbon quantification methods, and monitoring systems not only result in low environmental effectiveness but also increase the risk of over-crediting and erode investor confidence. Additionally, the absence of equity and ecological considerations in protocol design continues to undermine the long-term potential of forest projects. Therefore, it is crucial to adjust these systems to enhance transparency, scientific credibility, scalability, and, importantly, ensure

the participation and rights of stakeholders, particularly IPLCs and smallholders.

4. Recommendations for Improving Carbon Project Evaluation Systems

Recent studies on global FCM assessment systems have highlighted several notable trends in the design and implementation of protocols and standards. These proposals aim to enhance the climate effectiveness of FCM, while improving transparency, organizational legitimacy, and social equity throughout the carbon value chain. Current solutions indicate a clear shift from a singular technical approach to an integrated evaluation model, combining technology, transparent governance, and social equity, to increase the legitimacy and practical effectiveness of FCC across different levels [2, 12, 15, 49].

4.1. Clarifying Policy Roles and the FCM Structure

Li & Zhang [15] propose three key policy directions for reforming FCM systems, emphasizing the need to clearly define the role of FCC within national cap-and-trade mechanisms. If FCC is considered equivalent to emission reductions from industry, they should be freely traded at a unified market price. Conversely, if there are distinctions in reliability or actual impact, two separate markets should be established with distinct control and pricing mechanisms. Clarifying this role is fundamental for designing coherent and effective management systems at national, regional, and project levels.

4.2. Improving Carbon Quantification Methodologies to Enhance FCC Quality

There is a discernible shift from flexible to precautionary carbon quantification methodologies aimed at mitigating over-crediting, which undermines the system's integrity and climate efficacy [11, 12]. To enhance integrity, suggested frameworks prioritize the calibration of baselines against historical management records or the adoption of dynamic baselines. Furthermore, it is recommended that intensive harvesting scenarios be permitted only under distinct, stringent verification protocols [12]. Additionally, supplementary tools such as "regulatory surplus tests" or "investment analysis" [49] should be enhanced with greater transparency and independent verification to limit fraud and adverse selection at the project level.

4.3. Ensuring Permanence Through Risk Assessment and Buffer Pool Management

The FCC durability is frequently compromised by natural hazards and human interference, creating a significant risk of reversal. Haya et al., [12] and Pan et al., [49] argue that current buffer pool systems are inadequate defenses against these threats. Consequently, proposed solutions emphasize a shift toward more robust capitalization of buffer pools, grounded in realistic risk assessments and temporal cycles, alongside the adoption of active silvicultural practices like controlled burning [2, 61]. To enhance precision, the integration of dynamic tools such as the Forest Carbon Futures Tool allows for spatiotemporally adjusted credit allocation and periodic risk re-evaluation.

4.4. Integration of Multi-tiered, Cost-effective, and High-precision MRV Systems

While MRV systems constitute the bedrock of carbon market transparency and integrity, current standards (e.g., VCS, CAR, ACR) are often hindered by prohibitive costs, variable accuracy, and limited applicability to small-scale projects despite their differing monitoring cycles [49]. Consequently, there is a paradigm shift toward integrated, multi-tiered MRV frameworks that synergize advanced technologies, such as LiDAR, UAVs, remote sensing, and modeling with robust field data [2, 49]. To optimize these systems, future protocols must prioritize the regional standardization of biomass quantification, the deployment of open-

source tools, and the enhancement of community-based monitoring at the local level [62].

4.5. Harmonizing Carbon Leakage Risk Assessment and Developing Region-specific Coefficients

The credibility of the carbon credit system is currently threatened by the inadequate assessment of leakage, where mitigation efforts in one area displace emissions to another. Haya et al., [12] and Pan et al., [49] argue that existing methodologies, which utilize average, static leakage factors, significantly weaken credit integrity. Addressing this requires a methodological overhaul: moving toward verifiable, regionally distinct coefficients that incorporate periodic updates and reverse leakage calculations. Additionally, adopting technical solutions like credit stacking can ensure that crediting mechanisms accurately track the temporal fluctuations of carbon sequestration [63, 64].

4.6. Enhancing the Integration of Socio-environmental Benefits and Community Engagement

A pivotal trend in the evolution of carbon protocols is the deep integration of socio-environmental objectives, a shift designed to enhance not only system legitimacy but also equity and operational efficacy. Current standards exemplify this approach: the Climate Action Reserve imposes rigorous biological criteria, while Plan Vivo mandates that at least 60% of revenues be shared with local communities [49]. By incorporating metrics for biodiversity, indigenous culture, and livelihoods, these frameworks foster the creation of "ethical credits", which are increasingly favored by the market. However, Haya et al., [12] caution that without appropriate pricing policies and explicit market demand for high-quality assets, developers may lack the sufficient economic incentives required to sustain long-term forest management.

4.7. Scale-based Flexibility and Regional Standardization

Recognizing that a "one-size-fits-all" approach is no longer appropriate, recent scholarship advocates for stratified assessment frameworks. Haya et al., [12] propose tailoring baseline and additionality requirements to the specific profiles of industrial versus community stakeholders. Concurrently, minimizing transaction costs for smaller projects via simplified MRV and permanent plot sampling is recommended to enhance feasibility [49]. Ultimately, a shift toward regional standardization is essential to maintain rigorous verification standards while accommodating local socio-ecological nuances.

4.8. Reinforcing Legitimacy and Harmonizing Standards

Given that forest carbon standards operate primarily within the voluntary market, often devoid of legally binding mandates, their legitimacy is of paramount importance. Merger and Pistorius [7] advocate for a standard-setting process grounded in interdisciplinary consultation, active civil society engagement, and independent verification. Concurrently, the harmonization of core protocol elements, specifically MRV, social impact assessments, and verification mechanisms, is essential to mitigate market fragmentation and enhance operational efficiency. However, scholars caution that such standardization must be carefully calibrated to avoid stifling technical innovation or impeding healthy market competition [2, 7].

5. Conclusion

This study elucidates critical deficiencies within global forest carbon assessment frameworks and identifies essential pathways for reform to enhance both the efficacy and sustainability of carbon credits. A comprehensive analysis of implementation

across three distinct scales (national, regional, and project) reveals that each tier operates under a unique design logic aligned with specific policy mandates and mitigation objectives. These range from national emission management within compliance regimes, such as the NZ ETS, to the generation of financial incentives for small-scale conservation in voluntary markets, exemplified by Plan Vivo, CAR, and VCS.

Nevertheless, the analysis uncovers significant systemic limitations. The absence of cross-scalar standardization, coupled with excessive methodological flexibility, particularly at the project level, exacerbates the risk of over-crediting, thereby compromising environmental integrity. Furthermore, current MRV systems are characterized by prohibitive costs, technical complexity, and insufficient independent auditing, effectively marginalizing small-scale initiatives. Crucially, dimensions of social equity, land tenure, and community engagement remain under-addressed, while ecological co-benefits frequently lack robust quantification.

Addressing these challenges necessitates a paradigm shift toward integrated assessment frameworks that synergize technical precision, governance transparency, and social equity. Key remedial strategies include the refinement of quantification methodologies, the calibration of buffer pools based on empirical risk, the deployment of cost-effective, multi-tiered MRV architectures, and the adoption of regional standardization. Ultimately, clarifying the role of forest credits within national and global carbon architectures is pivotal for constructing a system that is scale-flexible yet rigorous in consistency, transparency, and credibility across the entire value chain.

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Appendix 1. Comparative analysis of FCC frameworks

Source	Market	Scale	Activities	Additionality	Permanence	Leakage	MRV
Li & Zhang (2024) [15]	New Zealand ETS (Compliance)	National	Afforestation, IFM, Reforestation	Stock change vs. Averaging accounting (long-term cycle)	50-yr clear-fell ban; NZU surrenders for violations	Sector-wide (Direct)	Periodic emission returns; mandatory audits. Two main accounting methods: Stock change accounting and Averaging accounting
	Australia; ACCUs (Compliance)	Project	Afforestation, Avoided conversion, IFM	Three-step test: Newness, Regulatory, Government	Choice: 25 vs. 100 yrs (25-yr discount)	Not publicly available	FullCAM modeling & periodic audits
	California; CARB (Compliance)	Project	Reforestation, IFM, Avoided conversion	100-yr projection; Financial feasibility; Common practice	Buffer pool; Credit invalidation for intentional reversal	20% (Activity & Market)	6-step CAR methodology; field surveys
	China; CCER (Compliance)	Project (Potential for National expansion)	Afforestation, IFM	BAU scenario; Carbon above baseline	Limited; Retention = Crediting period	Not publicly available	Accredited 3rd-party verification
	USA; RGGI (Compliance)	Regional	Afforestation, Avoided land conversion, IFM, Reforestation	100-yr model; Regulatory & Performance tests	100-yr duration; Allowance cancellation for reversals	Activity-shifting accounted	Life-cycle MRV; accredited state verifiers
Haya et al. (2023) [12]	USA, ARB (Compliance & Voluntary)	Project	IFM	Standardized approach; deviation from 100-yr baseline	100 years	20% Market (Inconsistent timing)	Stock change; IPCC 2019 alignment; Allometric equation
	USA ACR (Voluntary)	Project	IFM	NPV-maximization baseline; Barrier & Regulatory tests	40–100 years	0–40% Market (Consistent timing)	Stock change; 5-yr reporting; 10-yr inventory.
	USA CAR (Voluntary & compliance)	Project	IFM	100-yr counterfactual; mandates legal compliance & financial feasibility; Common Practice floor for initial stocks	100-years	20% market rate; Inconsistent timing; Positive leakage permitted only for credit recovery	Stratified/systematic random plots; CARIT tools; includes biomass, dead wood, & HWP; small pool exclusion allowed
	Mexico CAR (Voluntary)	Project	IFM	Standardized; Baseline = Initial carbon stocks; all sequestration exceeding initial stocks is additional	1–100 yr proportional model (1% credit yield per year of commitment)	20% market rate; Consistent timing; Positive leakage permitted	Stock inventory via allometric equations; Ton-year accounting utilized for durability alignment; Localized pool selection
	Australia, Canada, China, Malaysia,	Project	IFM	Project-specific; Financial/Barrier tests	20 years	0–70% market rate (methodology-specific: VM0003/05/1	Stock-change via plot-based inventory; Allometric biomass

Source	Market	Scale	Activities	Additionality	Permanence	Leakage	MRV
	Romania, USA; VCS (Voluntary)					0/12); Generally accounted via harvest emission deductions	estimation; Flexible pool inclusion (AGB, BGB, HWP, Soil)
Pan et al., (2022) [49]	VCS (Voluntary)	Multi-scale (National, Regional, Project)	All (AR, REDD, IFM)	Investment, Barrier, & Common practice tests	Non-permanence risk; Buffer withholding.	Activity shifting and market effects.	GIS & Remote sensing integration; 3rd party verification
	ACR (Voluntary)	Primarily project level	All (AR, REDD, IFM)	Legal regulatory surplus, barrier tests, and common practice assessment.	ACR Tool-based risk assessment; Buffer pool determination	Monitor activity-shifting; Estimation of market-effect leakage	GIS and remote-sensing integration with field data; 5-yr verification frequency; 3rd-party accredited audit
	CAR (Voluntary)	Primarily project level	All (AR, REDD, IFM)	Legal requirement and performance standard test	Reversal risk rating; Buffer pool allocation	Integrated leakage factors (secondary effects) in net credit quantification	Annual reporting for 100 years post-issuance; GIS/Remote sensing & field data; 3rd-party accredited verification at each period
	Plan Vivo (Voluntary)	Primarily project level	All (AR, REDD, IFM)	Regulatory surplus and barrier analysis; Socio-economic baseline requirement	Risk-adjusted buffer (10–20% min. contribution)	Comprehensive identification of all potential sources	Annual reporting; GIS/Remote sensing & field monitoring; 5-yr verification cycle by accredited 3rd parties