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A Conceptual Blockchain Architecture for Ecological–Financial Risk Management in Blue Carbon Markets

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Abstract

Blue carbon finance is constrained by unreliable ecological data, information asymmetry, and high compliance demands. This study develops an ecological–financial governance interface within a conceptual six-layer blockchain architecture for blue carbon finance. The design combines versioned on-chain and off-chain records with a multi-party signature approval workflow and five contract modules. It is intended to support traceable hand-offs among ecological monitoring, methodology-governed accounting, MRV, credit-state management, and financial risk review. The contribution is a defined sequence from versioned ecological evidence to accounting review, credit-state records and authorised financial decisions. A synthetic worked example makes these decision rules explicit while retaining independent MRV and registry authority.

Keywords: blue carbon finance; blockchain architecture; smart contract; ecological–financial risk coupling; information asymmetry; sustainable development

1. Introduction

Sustainable development requires that climate action be advanced in synergy with ecosystem conservation and socio-economic well-being [1,2]. Blue carbon sinks, comprising marine ecosystems such as mangroves, salt marshes, and seagrass beds, have become a key strategy for addressing climate change and achieving sustainable development, owing to their exceptionally high carbon sequestration efficiency, long-term carbon storage capacity, and multiple synergistic ecological benefits [3]. Blue carbon ecosystems store carbon in biomass and sediments, with sequestration and storage varying across ecosystem types; they also provide coastal protection, biodiversity maintenance, and fishery resource conservation [4–6]. However, the large-scale development of blue carbon projects faces a severe financing bottleneck [7]. Long-term permanence risks can further constrain the financing opportunities available to mangrove projects [8]. Although voluntary carbon markets and alternative financing mechanisms are being explored globally, case studies identify financial, institutional and implementation barriers to blue carbon projects [9].

Blue carbon finance has become an indispensable pathway to resolve the financing dilemma [10]. By integrating financial instruments such as credit, bonds, insurance, and

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carbon credit trading, it converts the ecological value of blue carbon into tradable financial assets, thereby providing sustainable funding for conservation and restoration projects [11]. A certain institutional foundation has been established. The EU's 2021 Sustainable Carbon Cycles communication integrated coastal wetlands into the carbon removal policy framework [12], while the amended Land Use, Land-Use Change and Forestry (LULUCF) framework includes managed wetlands in land-sector accounting; project-credit eligibility follows programme-specific validation [13,14]. Meanwhile, Article 6.2 of the Paris Agreement provides for cooperative approaches involving internationally transferred mitigation outcomes under applicable party authorisation and accounting arrangements [15]. These policy developments and institutional implementation pathways [16], while supporting the development of blue carbon finance, also converge on three core prerequisites for its sound development: data credibility, risk controllability, and transparent compliance. Specifically, the large-scale deployment of blue carbon finance currently faces three major obstacles. First, insufficient data credibility constitutes a financing barrier [17]. Blue carbon accounting requires long-term ecological observations and ecosystem-specific models [17,18]. Related research on blockchain-enabled finance examines green-finance applications, ESG performance, transaction costs and coordination [19–22], informing the design of information coordination. Traditional offline recording and manual verification methods are unable to avoid problems such as data tampering and over-reporting, and lack a unified trusted mechanism for evidence preservation and traceability [18]. Financial institutions, unable to verify the authenticity and accuracy of the underlying carbon sink assets, hesitate to extend credit, directly leading to financing difficulties for blue carbon projects. Second, information asymmetry can easily trigger multiple risks and undermine market trust. There is a severe information barrier between project proponents and capital providers, and this imbalance can breed moral hazard. For example, project proponents might conceal the degradation of carbon sinks or use the same carbon sink asset as collateral repeatedly, exploiting information asymmetry to engage in the "double-selling" of carbon credits. This prevents the market from establishing effective risk-pricing mechanisms and dampens the willingness of private capital to participate [22,23]. Third, governance and implementation procedures remain demanding. Research on mangrove carbon-sink development identifies institutional and collective-action challenges that can affect project implementation [24].

Blockchain technology, with its characteristics of distributed ledgers, immutability, and automatic execution of smart contracts, provides a technical possibility to address the above three barriers [25,26]. In the context of environmental compliance in maritime industries, a blockchain framework has been proposed for traceability and fraud prevention in aquaculture [27]. Specifically, distributed ledgers maintain the same data record across multiple nodes, allowing committed carbon records to be compared across participants and later changes to be traced [28]. Authorised nodes can cross-check committed versions, while ecological measurement quality remains subject to the monitoring and MRV process. Recorded generation, transfer and trading events form a replicated history, with authorised changes recorded as attributable state transitions. This supports the detection of conflicting records and encumbrances within participating systems, a governance function also studied in forestry and inventory finance [29,30]. Smart contracts can encode business logic, including ecological protection norms, carbon accounting standards, and financial transaction rules, into automated, condition-triggered execution and real-time verification. After the required verification and registry decisions, a smart contract can record issuance receipts and execute authorised settlement instructions. Deterministic checks support traceable compliance records, while the competent programme and contractual authorities retain their decision roles [31]. Existing studies address carbon tracking and adaptive

pledge finance [32,33]. The present design focuses on the specific hand-off from changing blue carbon evidence to methodology-governed review and authorised financial action.

To fill this research gap and provide a systematic solution, this study is driven by two core research questions (RQs):

- RQ1: How can a blockchain-based architecture be systematically structured to resolve the prevalent issues of data unreliability, high compliance costs, and information asymmetry inherent in blue carbon finance?
- RQ2: How can smart contracts be technically designed to dynamically adapt to the spatiotemporal evolution and real-time carbon sink fluctuations of blue carbon ecosystems, thereby coupling ecological monitoring with financial risk management?

To address these questions, this paper specifies an ecological–financial governance interface within a six-layer blockchain architecture tailored to blue carbon finance. The design specifies on-chain and off-chain storage, a multi-party signature approval workflow, and five contract modules that together support traceable information hand-offs from ecological monitoring to financial settlement. The dynamic indicator-adjustment and ecological–financial risk-coupling module is designed to receive signed and versioned ecological-data submissions, initiate proposed accounting updates, and communicate risk signals to authorised participants. Accredited MRV bodies assess ecological evidence, registries govern credit status, and the competent parties authorise financial decisions. The paper contributes a structured framework for analysing how blockchain-supported governance could reduce information asymmetry and make ecological and financial decision points more auditable.

The remainder of this paper is organised as follows: Section 2 reviews the literature on blue carbon finance and blockchain applications. Section 3 establishes the fundamental modelling and accounting framework for blue carbon finance, defining the participants and presenting the carbon sink accounting methodology. Section 4 designs a dynamically adaptable six-layer blockchain architecture and proposes the corresponding consensus mechanism, storage scheme, and smart contract system. Section 5 provides a discussion of the results, analysing the feasibility and challenges of the proposed architecture, as well as policy implications. Section 6 concludes the paper, identifies the limitations, and outlines directions for future research.

2. Literature Review

2.1. Blue Carbon Finance

As an extension of green finance into the marine realm, blue carbon finance mobilises private capital for coastal ecosystem conservation through a range of financial instruments, and has attracted growing scholarly and policy attention. Existing research can be broadly categorised into two streams: theoretical mechanism exploration and practical application. On the theoretical front, Li and Liu developed a four-tier typology of blue carbon finance—spot, trading instruments, financing instruments, and supporting instruments—and systematically elucidated the operational logic of each category, offering a comprehensive financial solution for blue carbon project development [11]. Vanderklift et al. examined the constraints and opportunities facing market-based financing for blue carbon restoration and conservation, identifying private investors' expectations of reliable returns, risk quantification and management, supply-chain dynamics, and regulatory uncertainty as key limiting factors [7]. Friess et al. observed that current blue carbon projects tend to be small-scale and suffer from double-counting and high verification costs, and advocated complementary non-credit financial instruments to provide stable and substantial funding streams [34]. Zheng et al. further cautioned that persistent shortcomings in market integrity, governance frameworks, and long-term project man-

agement, compounded by climate-driven risks such as sea-level rise and altered storm regimes, undermine core integrity attributes including additionality, permanence, and leakage control, thereby constraining the contribution of blue carbon markets to climate mitigation targets [35]. On the practical application side, Shiiba et al. took the Seychelles blue bond as a case study to probe the challenges and opportunities of blue finance, and proposed a regulatory-oriented financial mechanism that connects diverse stakeholders and enhances incentives for both private investment and public donation [36]. Kuwae et al. reviewed blue carbon offset credit projects in Japanese seagrass, macroalgal beds, and macroalgal aquaculture, concluding that financing is critical to implementation and that project viability hinges on the effective use of both international and domestic financial resources [37]. Wang and Lian focused on marine ranching as a blue finance application context, employing grounded theory and fuzzy-set qualitative comparative analysis (fsQCA) to identify the core enabling dimensions of blue finance—namely policy, market infrastructure, product innovation, service provision, capacity building, and ecosystem development. Their findings reveal a multi-factor synergistic pathway through which blue finance advances sustainable development, providing an empirical basis for regionally differentiated policy design [38].

2.2. Exploring the Application of Blockchain Technology in Carbon Finance

Faced with challenges related to data authenticity, transaction transparency, and compliance auditing in carbon markets, blockchain technology, with its characteristics of decentralisation, immutability, and smart contracts, has gradually become a research hotspot in the field of carbon finance [39,40]. With respect to carbon market mechanisms and distributed settlement, existing studies have systematically reviewed trading mechanisms such as carbon allowances, CCERs, and green certificates, and have analysed the feasibility and limitations of blockchain-based carbon trading from the perspectives of system design, consensus mechanisms, smart contracts, access restrictions, and encryption technologies [41]. In terms of specific technical design, related studies address business–finance integration as well as technical design [42]. Merlo et al. pointed out that blockchain technology can automate the verification and certification process through smart contracts, enhancing transparency, reducing fraud, and ensuring compliance [43]. Khan et al. reviewed blockchain applications in carbon-emission trading [44]. Khan, Tahmid and Adar describe Blockchain–AI–IoT Carbon Governance (BAIC-Gov) in their undergraduate thesis [45]. This proposed architecture combines blockchain, smart contracts, IoT observations and AI-based monitoring to organise carbon credit and compliance workflows, including legacy trading-system interoperability, anomaly detection and traceability [45]. Abiodun et al. summarised the application of blockchain technology in carbon trading markets, reviewed the reported functions and implementation challenges of blockchain-driven carbon trading solutions, and proposed a comprehensive framework design for future technological evolution [46].

Evolutionary game analysis of blockchain in carbon sink trading shows that blockchain technology can increase the willingness of demand-side participants to engage in transactions, thereby promoting the healthy development of the carbon sink market [47]. Research on information and communication technologies (ICTs) examines blockchain, sensing and AI across carbon sink economics and engineering, linking monitoring, valuation and transaction functions [48]. Specifically in the blue carbon domain, some scholars have begun to explore pathways for applying blockchain technology. Zhao et al., based on the theoretical framework of Blockchain 3.0, designed a blue carbon system architecture under a peer-to-peer (P2P) trading model and analysed the service provision mechanisms of various participants in the production, circulation, and trading processes of blue carbon [49].

Wahsheh proposed a compliance-aware cryptographic framework to ensure end-to-end security of blue carbon accounting. The framework binds IoT sensing devices to national public key infrastructure (PKI) identities, generates audit-ready cryptographic evidence in line with MRV workflows, uses the Elliptic Curve Digital Signature Algorithm (ECDSA) to ensure authenticity and non-repudiation, and achieved a 100% tamper detection rate in simulated attack tests [50].

The above studies indicate that insufficient data credibility, information asymmetry, and regulatory uncertainty constrain blue carbon finance. Blockchain is a potentially useful governance tool, but its contribution depends on credible MRV, appropriate institutional controls, and clear allocation of accountability. Existing applications often address data certification or transaction traceability in isolation. The present study therefore develops a conceptual full-lifecycle architecture that explicitly includes versioned ecological inputs and configurable financial risk responses. The framework specifies the technical interfaces, decision authorities and evaluation requirements for dynamic ecological–financial coupling. Supplementary Materials S1 illustrates the defined rule sequence.

2.3. Comparison with Closely Related Architectures

Table 1 compares closely related architectures. Supplementary Materials S1 provides a descriptive comparison with Verra digital MRV, the Toucan Puro bridge and KlimaDAO retirement contracts across registry, ecological-event and financial-review functions [51–55].

Table 1. Conceptual comparison of closely related blockchain architectures for blue carbon and carbon-market applications.

Dimension	Blue Carbon Trading Architecture [49]	IoT/Blockchain Carbon-Market Literature [44–46]	Cryptographic Blue Carbon Monitoring [50]	Present Conceptual Framework
Primary scope	Blue carbon market structure and P2P trading	Carbon-market data and workflow automation	Secure monitoring evidence	Full-lifecycle governance for blue carbon finance
Contract and registry interface	Project and trading functions	IoT-linked credit workflows	Monitoring evidence; registry external	Methodology records; official registry receipt
Ecological-event review	Not the stated focus	Anomaly detection proposed; blue carbon finance not its focus	Monitoring-security focus	Proposed trigger for accounting and risk review
Financial function	Includes trading, lending and finance	Credit and compliance workflows	Not the stated focus	Credit-state, pledge, and risk-review interfaces
Authorisation and consensus	Event-specific authority not specified	Detailed legal authority not specified	PKI and signature assurance	Role-specific approval; separate ledger ordering
Validation status	As reported in the cited study	As reported in the cited studies	Simulated attack tests reported in the cited study	Conceptual specification; synthetic walkthrough in Supplementary Materials S1

Accordingly, the proposed contribution is a governance interface that links versioned ecological data, documented accounting rules, credit-state transitions, and authorised financial risk review. This interface is specified through review states and decision authorities; Supplementary Materials S1 illustrates its operation.

3. Fundamental Modelling and Accounting Framework for Blue Carbon Finance

3.1. Participants and Their Roles in Blue Carbon Finance

Clearly defining the participants and business processes of blue carbon finance is a fundamental prerequisite for applying blockchain technology to enable trusted operation across the entire blue carbon finance chain. Blue carbon finance involves multiple participants, including blue carbon project proponents, third-party MRV verification bodies (MRV stands for Monitoring, Reporting and Verification, which is the core technical support mechanism for carbon accounting and carbon credit systems), regulatory authorities, blue carbon trading institutions, and financial institutions and carbon credit buyers [56]. The specific roles of these five types of participants in the accounting and operation of blue carbon finance are illustrated in Figure 1, and are detailed as follows:

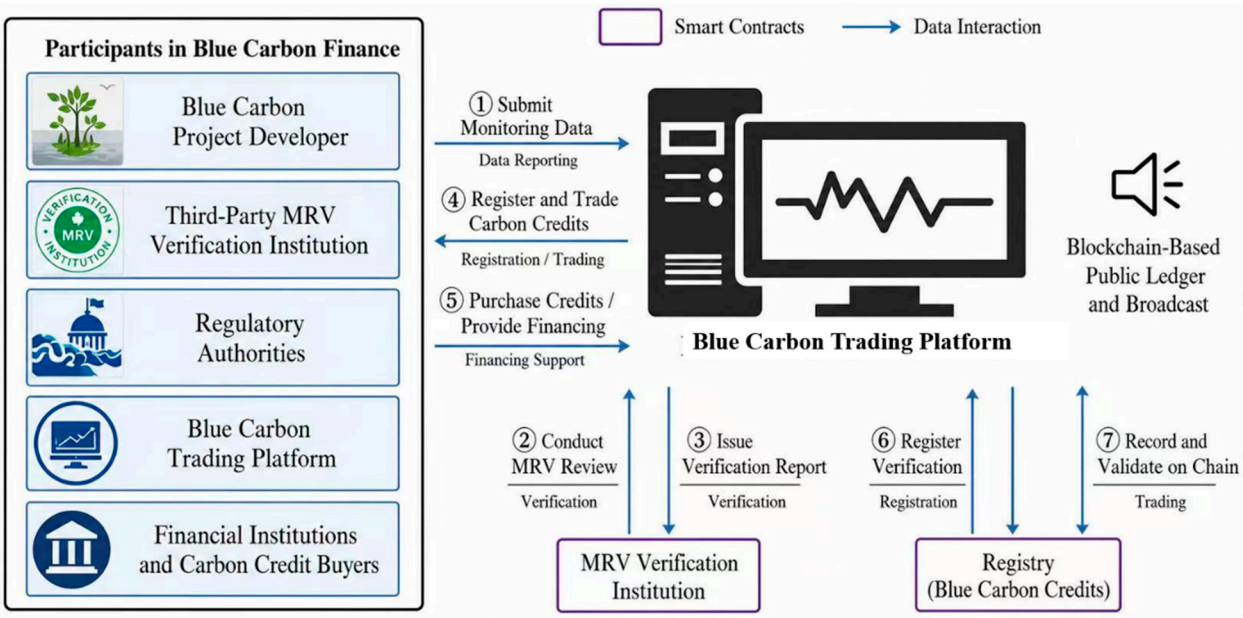

Figure 1. Conceptual participants and business processes in blue carbon finance.

(1) Blue carbon project proponents refer to the entities implementing conservation and restoration projects of blue carbon ecosystems such as mangroves, salt marshes, and seagrass beds. They are responsible for project development, daily operation and maintenance, quantification of carbon sink enhancement benefits, as well as the collection and accounting reporting of multi-source monitoring data.

(2) Third-party MRV verification bodies are the verification entities for blue carbon credits. They undertake the implementation of blue carbon accounting methodologies and verification standards, conduct independent validation of project qualifications and accounting data, and provide technical support for the issuance of blue carbon credits.

(3) Regulatory authorities cover relevant departments such as marine affairs, ecological environment, development and reform, and financial supervision. They are responsible for the formulation of blue carbon accounting methodologies and verification standards, project qualification review, full-process compliance supervision, as well as the issuance and registration management of blue carbon credits.

(4) Blue carbon trading institutions serve as the trading and registration platforms for blue carbon credits, providing services such as electronic registration, order matching, clearing and settlement, and pledge registration of blue carbon credits. They act as the central hub connecting blue carbon project proponents with carbon credit buyers.

(5) Financial institutions and carbon credit buyers include banks, insurance companies, securities firms, funds, and other financial institutions, as well as enterprises and organisations with carbon neutrality needs. These participants can either offset their emissions by purchasing blue carbon credits or develop diversified financial products based on blue carbon credits—such as pledge loans, blue carbon insurance, carbon bonds, and asset-backed securities (ABS)—thereby providing financial support for blue carbon projects.

3.2. Accounting Methodology for Blue Carbon Sinks

Accurate, methodology-specific quantification is a prerequisite for blue carbon finance [56–58]. Equations (1)–(3) adopt the baseline, project and net balances in Verra VM0033 Methodology for Tidal Wetland and Seagrass Restoration v2.1, source Sections 8.1, 8.2 and 8.5.1, Equations (18), (69) and (85), respectively [59]. This methodology covers eligible tidal-wetland restoration, including qualifying mangrove, tidal-marsh and seagrass activities. Project boundaries, carbon pools, monitoring intervals, uncertainty and optional fire modules follow that methodology. Each project record identifies its eligible activity and applicable methodology profile.

3.2.1. Baseline Scenario Emissions

The baseline scenario refers to a reasonably representative scenario of the natural changes in carbon stocks within the project boundary in the absence of any blue carbon project intervention. Its carbon emission accounting mainly covers three components: changes in biomass carbon pools, changes in soil carbon pools, and emissions from fossil fuel use in project-related activities. Equation (1) reproduces the aggregate balance in VM0033 v2.1, Equation (18) [59]:

$$GHG_{BSL} = GHG_{BSL-biomass} + GHG_{BSL-soil} + GHG_{BSL-fuel} \quad (1)$$

where

GHG_{BSL} = Net CO_2e emissions in the baseline scenario up to year t: t CO_2e.

$GHG_{BSL-biomass}$ = Net CO_2e emissions from biomass carbon pools in the baseline scenario up to year t: t CO_2e (*).

$GHG_{BSL-soil}$ = Net CO_2e emissions from the soil organic carbon pool in the baseline scenario up to year t: t CO_2e (**).

$GHG_{BSL-fuel}$ = Net CO_2e emissions from fossil fuel use in the baseline scenario up to year t: t CO_2e.

(*) Refers to the change in carbon pool stored in the living biomass of plants between time (t) and some time in the past (for example t = 2020 and 2010); (**) refers to the change in carbon pool stored in the soil between time (t) and some time in the past. If the change is negative this is referred to as sequestration.

3.2.2. Project Scenario Emissions

The project scenario refers to the actual changes in carbon pools within the project boundary after the implementation of the blue carbon project. Its accounting can include biomass, soil, prescribed burning and fossil fuel use where applicable. Equation (2) follows VM0033 v2.1, Equation (69); a burning term is zero when the relevant activity does not apply [59]:

$$GHG_{WPS} = GHG_{WPS-biomass} + GHG_{WPS-soil} + GHG_{WPS-burn} + GHG_{WPS-fuel} \quad (2)$$

where

GHG_{WPS} = Net CO_2e emissions in the project scenario up to year t: t CO_2e.

$GHG_{WPS-biomass}$ = Net CO_2e emissions from biomass carbon pools in the project scenario up to year t: t CO_2e.

$GHG_{WPS-soil}$ = Net CO_2e emissions from the soil organic carbon pool in the project scenario up to year t: t CO_2e.

$GHG_{WPS-burn}$ = Net CO_2e emissions from prescribed burning in the project scenario up to year t: t CO_2e.

$GHG_{WPS-fuel}$ = Net CO_2e emissions from fossil fuel use in the project scenario up to year t: t CO_2e.

3.2.3. Leakage Accounting

Leakage refers to a measurable and attributable increase in greenhouse gas emissions or a decrease in carbon stocks outside the project boundary that results from project implementation. Its boundary, estimator, monitoring plan, uncertainty treatment, and any deduction must be specified by the applicable methodology. Potential pathways may include activity displacement, market-mediated effects, or ecological effects outside the project boundary.

3.2.4. Net Blue Carbon Sink Accounting

$$NER_{RWE} = GHG_{BSL} - GHG_{WPS} + FRP - GHG_{LK} \quad (3)$$

where

NER_{RWE} = Net CO_2e emission reductions from Restoring Wetland Ecosystems (RWE): t CO_2e. Equation (3) follows VM0033 v2.1, Equation (85) [59].

GHG_{BSL} = Net CO_2e emissions in the baseline scenario: t CO_2e.

GHG_{WPS} = Net CO_2e emissions in the project scenario: t CO_2e.

FRP = Fire reduction premium (net CO_2e emission reductions from organic soil combustion due to rewetting and fire management): t CO_2e. This optional VM0033 term applies only to eligible rewetting and fire management. It is zero in the mangrove illustration in Supplementary Materials S1.

GHG_{LK} = Net CO_2e emissions due to leakage: t CO_2e.

3.2.5. Additionality and Permanence Adjustments

Additionality is an eligibility decision supported by programme-defined evidence. Under VM0033 v2.1, VMD0052 v2.0 uses regulatory surplus and positive-list eligibility [59,60]. The system records the supporting evidence, qualified reviewer, decision and rule version. The CDM combined tool referenced by VM0033 is used for baseline selection with its additionality elements excluded. The VMD0052 activity method governs additionality.

Non-permanence is handled through the applicable programme buffer and reversal arrangements. Equation (4) provides the authors' system interface to the approved programme buffer calculation. The eligible carbon-stock increment and assessed risk report determine the buffer record; measurement uncertainty is treated separately under VM0033 [59,61].

$$Q_{buf,p} = B_m(\Delta NER_{stock,p}, r_p) \quad (4)$$

where $Q_{buf,p}$ is the buffer contribution for monitoring period p (t CO_2e), B_m is the applicable programme calculation, $\Delta NER_{stock,p}$ is its eligible carbon-stock base, and r_p is the approved non-permanence risk report. The interface records the method, inputs, reviewer and effective date. The linked eligibility record stores the additionality decision and its evidence.

3.2.6. Blue Carbon Credit Equivalent Conversion

The uncertainty-adjusted accounting result is assessed through independent verification for the relevant monitoring period. Equation (5) is a bookkeeping interface for a new issuance request after the applicable buffer allocation. The VVB report records the verification decision. Issuance remains subject to the programme and registry decision [14,59].

$$Q_{net,p} = Q_{ver,p} - Q_{buf,p} \quad (5)$$

where $Q_{net,p}$ is the proposed new-issuance allocation, $Q_{ver,p}$ is the independently verified monitoring-period quantity after applicable uncertainty treatment, and $Q_{buf,p}$ is the corresponding buffer allocation (t CO_2e). Period quantities prevent repeated issuance of cumulative totals. The actual issued quantity and serials are taken from the registry receipt; subsequent buffer releases and reversals follow separate programme events.

3.2.7. Parameter Governance and Methodology Versioning

Accounting parameters follow the applicable methodology and programme rules. The weights, review thresholds, LTV cap, freshness limit and coverage cutoff in the worked example are illustrative design parameters. Table 2 identifies parameter sources, decision authorities and system roles.

Table 2. Governance sources, decision authorities, and system roles for key accounting and risk parameters.

Parameter or Decision	Source of Value or Rule	Decision Authority	Role of the Architecture
Additionality status	VM0033/VMD0052 eligibility evidence [59,60]	Accredited reviewer under programme rules	Record evidence, reviewer decision, and methodology version
Period buffer record $Q_{buf,p}$	Approved stock base and non-permanence report [59,61]	Programme or registry authority	Link the adjustment to its source and effective date
Verified period quantity $Q_{ver,p}$	Methodology uncertainty treatment; independent VVB report	Accredited VVB; programme/registry issuance authority	Keep calculation, verification and issuance distinct
Signature threshold q of n	Actor-specific approval policy; threshold within each role	Required VVB, registry or lender/holder role; see Supplementary Materials S1	Check required roles separately from ledger consensus
Ecological-review threshold	Declared change-detection rule; numerical illustration in Supplementary Materials S1	Authorised technical and governance body	Record the review state and route it to authorised decision makers
Proposed LTV adjustment	Governed risk model and contract; illustrative cap in Supplementary Materials S1	Financial institution and authorised governance pathway	Support an auditable review recommendation

Equations (1)–(3) retain the source methodology balances. Equations (4) and (5) identify author-defined interfaces for a programme-governed buffer record and a monitoring-period issuance request. Programme and registry decisions govern the resulting issuance event.

4. Dynamically Adaptable Blockchain Architecture and Smart Contract Design

4.1. Overall Blockchain Architecture Design

Blue carbon ecosystems show substantial spatiotemporal variation in carbon dynamics. This variation challenges financial systems that treat carbon credits as static assets.

To address this design problem, this paper proposes a conceptual six-layer architecture. The architecture is intended to support traceable ecological-data versioning, controlled workflow hand-offs, and configurable risk responses. The six layers organise established components; the paper-specific interface links ecological versions, accounting review, credit states and financial authority. The overall architecture is shown in Figure 2.

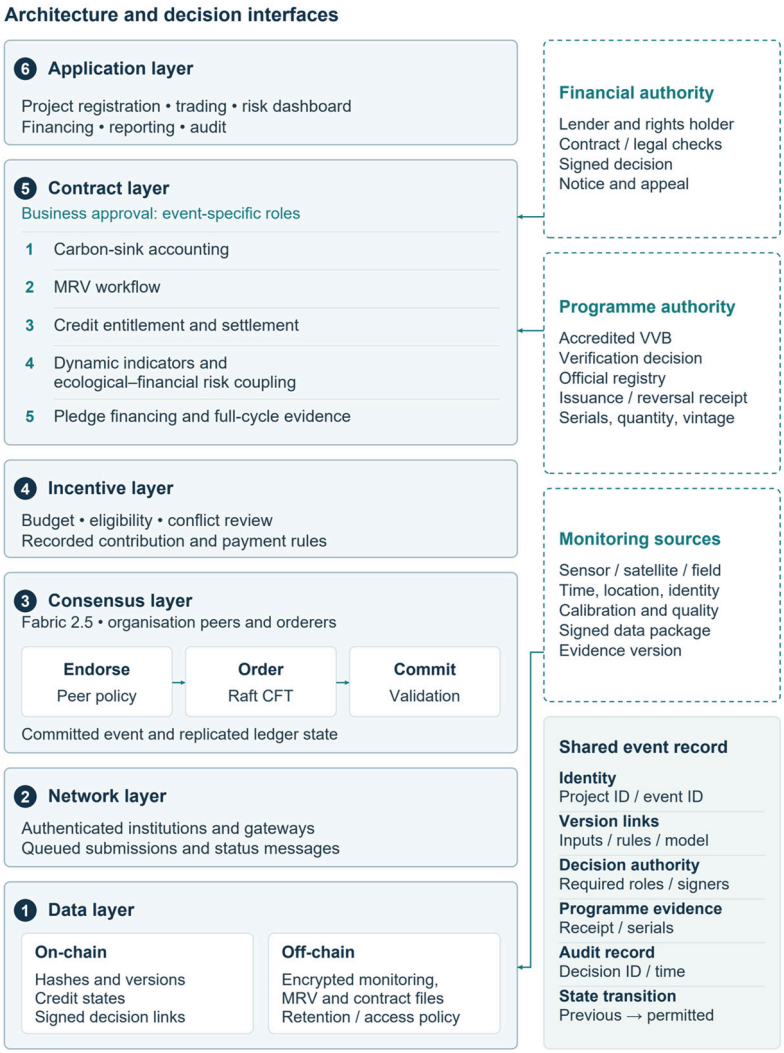

Figure 2. Conceptual blockchain architecture, trust boundaries, and governance layers for blue carbon finance.

(1) Data layer. This layer uses cryptographic hashes, hash chains, Merkle trees, time-stamps, and version identifiers to record the integrity and provenance of committed data. A hybrid on-chain and off-chain design is proposed because blue carbon monitoring involves large and evolving data packages. The ledger records selected metadata, hashes, signature references, ownership events, and ecological-state version identifiers. Raw time-series data, images, sampling records, and verification reports remain off-chain under defined retention, pinning, encryption, and access-control policies. A hash links the retrieved file to its committed version. MRV review assesses measurement accuracy, completeness and representativeness.

(2) Network layer. This layer is conceived as a permissioned peer-to-peer network that can accommodate monitoring devices, oracle services, regulatory nodes, trading institutions, and accredited verification bodies. Its performance under low bandwidth,

high latency, and intermittent connectivity should be evaluated empirically or by simulation before deployment claims are made.

(3) Consensus layer. The reference configuration uses Hyperledger Fabric 2.5 with Raft ordering under a crash-fault model [62]. Peer endorsement, ordering and valid state commitment are distinct from signed business approval [63]. A three-orderer cluster retains service with one crashed orderer and an available majority. The application policy requires the competent roles for each event; each required role has its own approval policy.

(4) Incentive layer. This layer proposes governance-approved incentives for data provision, anomaly reporting, and verification work. Eligibility, payment source, conflict-of-interest controls, performance criteria, and sanctions for poor-quality or misleading submissions must be specified before any incentive mechanism is implemented.

(5) Contract layer. The proposed design contains five grouped modules: carbon sink accounting; MRV workflow; carbon credit entitlement and settlement; dynamic indicator adjustment and ecological–financial risk coupling; and pledge financing with full-cycle evidence preservation. The modules record deterministic state transitions and authorised decisions. Accepted off-chain assessments supply ecological interpretation, and signed programme or contractual decisions authorise the relevant state transitions.

(6) Application layer. This layer could provide interfaces for project registration, credit issuance, trading, ecological risk dashboards, pledge-financing workflows, compliance reporting, and audits. Access rights, data confidentiality, decision authority, and manual-review routes should be defined for each participant. A dashboard may display versioned ecological indicators and recorded response decisions, but its outputs should be interpreted within the uncertainty and governance limits of the underlying data.

4.2. Asynchronous Approval Workflow and On-Chain/Off-Chain Collaborative Storage

Blue carbon finance involves dispersed participants, complex monitoring environments, intermittent connectivity, and large data volumes. The design combines multi-party signature approval with on-chain and off-chain storage, informed by related carbon-accounting workflow research [64]. Deployment evaluation addresses security, operating cost, performance and institutional suitability.

4.2.1. Multi-Party Electronic Signature-Based Approval

Business signatures may be collected asynchronously, but ledger ordering and commitment follow the underlying protocol [62,63]. Registration requires proponent and programme acceptance evidence; MRV requires an accredited verifier; issuance follows the registry receipt. Transfer requires holder instructions and registry confirmation. A pledge requires holder and lender approval and a legally supported lock. Financial changes require the applicable lender/rights-holder decision, accepted technical evidence, contract checks and notice or appeal provisions. A q-of-n rule defines redundancy within each authorised role, and the event policy identifies every mandatory role. Supplementary Materials S1 gives the event matrix.

4.2.2. On-Chain/Off-Chain Storage with Temporal Version Management

Blue carbon records include large data packages such as time-series monitoring data, remote-sensing products, sampling records, and verification reports. The proposed hybrid storage design records hashes, signatures, selected metadata, ownership events, and ecological-state version identifiers on-chain [65]. Off-chain files require explicit retention, replication or pinning, encryption, access-control, key-custody, and version-management policies. Bidirectional references support integrity checks between an on-chain commit-

ment and the retrieved file. Source review and storage policies govern accuracy and availability. Temporal version identifiers should allow an auditor to identify the data package, methodology version, decision authority, and effective time associated with each accounting result.

4.2.3. Threat Model and Data-Assurance Boundaries

The proposed ledger is permissioned. Project proponents, accredited MRV bodies, regulators, trading institutions, and authorised oracle services have distinct signing and access roles. A submission coordinator relays messages to the required decision makers and ledger services. Application approval depends on the required role signatures; ledger finality additionally requires ordering and valid commitment [62,63].

The design treats compromised sensors, missing or delayed data, replayed submissions, conflicting observations, compromised keys, and colluding signatories as explicit threat cases. Proposed controls include device identity, signed telemetry, calibration and maintenance metadata, freshness checks, replay protection, multi-source reconciliation, key revocation, conflict-of-interest rules, challenge procedures, and human dispute resolution. These controls allocate data-assurance and incident-review responsibilities across the participating organisations.

4.3. Smart Contract Design for Dynamic Coupling of Ecology and Finance

Based on the proposed six-layer architecture, the paper specifies five grouped contract modules for the blue carbon finance workflow. They cover accounting; MRV workflow; credit entitlement and settlement; dynamic indicator adjustment and ecological–financial risk coupling; and pledge financing with evidence preservation. The first three modules organise data and authorised decisions. The latter two provide a configurable design for linking versioned ecological information to financial risk review.

4.3.1. Automatic Carbon Sink Accounting Contract

The accounting module is designed to execute deterministic, methodology-specific calculations from authorised and versioned inputs. Its inputs should include project metadata, boundary definitions, ecosystem type, methodology version, data-quality status, and signed data submissions. Any non-deterministic processing, such as remote-sensing retrieval or statistical estimation, must be completed and documented off-chain before its results are submitted. The module can record calculation inputs, parameter provenance, outputs, and a report hash. The accredited review decision records acceptance of the measurements and methodology profile.

4.3.2. MRV Record Validation and Review Contract

The MRV workflow module is intended to organise monitoring, reporting, and verification records. It can check deterministic conditions, such as signature validity, data completeness against a declared schema, methodology version, and consistency between on-chain commitments and submitted files. Assessments of baseline plausibility, additionality, investment feasibility, implementation barriers, common practice, and ecological interpretation require accredited human review under the applicable programme rules. The resulting review decision, evidence references, signatory identity, and any exception should be recorded as an auditable event.

4.3.3. Carbon Credit Entitlement and Trading Settlement Contract

This module combines carbon credit entitlement and trading settlement. Subject to an authorised MRV decision and applicable registry rules, it can record credit ownership, issuance vintage, verification identifier, ecological-data version, transfer, pledge lock, and

retirement status. The state model should prohibit double issuance, double pledging, transfer while locked, and retirement of an ineligible or previously retired credit. The legal effect of settlement and any treatment of ecological reversals remain subject to registry, contractual, and jurisdictional requirements.

4.3.4. Dynamic Indicator Adjustment and Ecological–Financial Risk Coupling Contract

The dynamic indicator-adjustment and ecological–financial risk-coupling module produces auditable financial-review states and recommendations from versioned ecological evidence under governed rules.

(1) Ecological-state awareness and parameter review. Authorised oracle services submit signed, time-stamped ecological data with version and quality metadata. Quality checks precede comparison with the previous accepted, season-matched state. A declared decline threshold initiates accounting review; an approved assessment creates a new ecological-state version and linked accounting result.
(2) Dynamic early-warning design. Accepted ecological indicators map to NORMAL, WATCH_REVIEW or HIGH_REVIEW. Incomplete, stale or conflicting evidence enters DATA_REVIEW for completion. Significant decline requests methodology-specific accounting review. Supplementary Materials S1 supplies the functional rules.
(3) Response to abnormal ecological events. A signed abnormal-event report initiates an alert, review status and evidence preservation. The authorised decision pathway records contractual and legal review, notice, and appeal or override procedures for any issuance freeze or financial remedy.
(4) Ecological health score and risk level. For illustration, $H = 0.5c + 0.3s + 0.2i$ combines normalised vegetation cover c, survival s and inundation suitability i. States are NORMAL ($H \geq 0.80$), WATCH_REVIEW ($0.60 \leq H < 0.80$) and HIGH_REVIEW ($H < 0.60$). A decline ≥ 0.10 requests accounting review; $0.60H$ supplies an advisory LTV cap for a separately authorised decision. Supplementary Materials S1 records these illustrative design parameters; deployment follows the approved project model.

Table 3 links ecological assessment to financial decisions incorporating vintage, uncertainty, liquidity, exposure and contractual terms. Supplementary Materials S1 provides the numerical walkthrough.

Table 3. Required definitions and permitted actions in the proposed ecological–financial risk-coupling workflow.

Conceptual Item	Required Definition Before Use	Permitted Action in the Proposed Architecture
Ecological-data package	Variables, spatial and temporal support, calibration status, uncertainty, and source signatures	Create a versioned, auditable submission
Change-detection rule	Accepted reference state; quality gate; decline threshold	Initiate accounting or expert review
Ecological health score	Normalised indicators, weights and uncertainty; example in Supplementary Materials S1	Provide decision support only
Risk signal	NORMAL, WATCH_REVIEW, HIGH_REVIEW or DATA_REVIEW	Notify authorised participants and request review
LTV or collateral action	Credit status, liquidity, contractual terms, legal enforceability, and approved risk model	Review first; apply only the permitted signed decision

Exceptional events, including a large ecological disturbance, material data uncertainty, or conflicting monitoring information, should place the affected record into a review state. An authorised contractual decision records the supporting review, notice and appeal or override route. Algorithm 1 illustrates a conceptual decision sequence. It specifies review triggers and authorised state transitions; the numerical walkthrough is supplied separately in Supplementary Materials S1.

Algorithm 1: Core Logic of Ecological–Financial Risk Coupling Contract

```
Input: Authorised, signed, time-stamped monitoring submissions D(t), associated
quality metadata, and governed decision rules
Output: Accounting-review request, risk-review state, advisory LTV, and separately
authorised decision record
function Evaluate_And_Couple(D(t))
if not Valid_Submission_And_Quality(D(t)) then
Record(DATA_REVIEW); Request_Evidence(); return
end if
health_score, risk_level = Calculate_Status(D(t))
accounting_review = Check_Decline(D(t), accepted_reference)
if Detect_Abnormal_Event(D(t)) then risk_level = HIGH_REVIEW
end if
Update_Dashboard(health_score, risk_level)
Store_Review_State(D(t).version, risk_level)
if accounting_review then
Request_Authorised_Accounting_Review(D(t))
Store_Review_Request(D(t).version)
end if
advisory_LTV = Recommend_LTV(health_score)
Open_Financial_Review(advisory_LTV, evidence_version)
if Receive_Signed_Decision() then
if Check_Roles_Evidence_Versions_And_Contract() then
Record_And_Apply_Authorised_Decision()
Record_Notice_Appeal_And_Override_Route()
end if
end if
end function
```

4.3.5. Pledge Financing and Full-Cycle Evidence Preservation Contract

The pledge-financing module records financing applications, credit locks, authorised loan decisions, repayments, and evidence-preservation events. Warehouse-receipt pledge finance provides an adjacent asset-record comparison [66]. A proposed loan-to-value adjustment should use a validated and governed risk model. That model should account for ecological uncertainty, credit vintage, reversal provisions, market price and liquidity, borrower exposure, and legal enforceability. A change in ecological status may generate an alert or review recommendation. Additional collateral, repayment, transfer restrictions, or liquidation should occur only through the applicable contractual, regulatory, and authorised decision pathway, with documented notice, appeal, and override procedures. The evidence-preservation function should record ecological-data versions, parameter changes, authorised decisions, and exceptions, while recognising that legal evidentiary status remains jurisdiction-specific.

4.3.6. Validation and Implementation Roadmap

Supplementary Materials S1 provides a synthetic mangrove-restoration walkthrough from signed submission through quality checks, ecological-state review and an authorised financial decision. The execution traces the defined rules and authorised transitions. Prototype deployment, adversarial testing and comparison with conventional MRV or registry workflows can evaluate operational performance against the stated design and governance requirements.

Future validation should report the chosen system configuration, workload assumptions, transaction latency, throughput, storage overhead, signature-finalisation time, failure recovery, operating cost, and an explicit baseline. Risk-coupling evaluation should also report parameter calibration, sensitivity, false-positive and false-negative consequences, and outcomes against a static risk-management benchmark.

4.4. Business Process of Blockchain-Enabled Blue Carbon Finance

The workflow links the participants and accounting framework in Section 3 to the architecture, signature and storage design, and contract modules in Section 4. It covers registration, monitoring, accounting, MRV review, credit entitlement and trading, ecological–financial review, and retirement or evidence preservation (Figure 3).

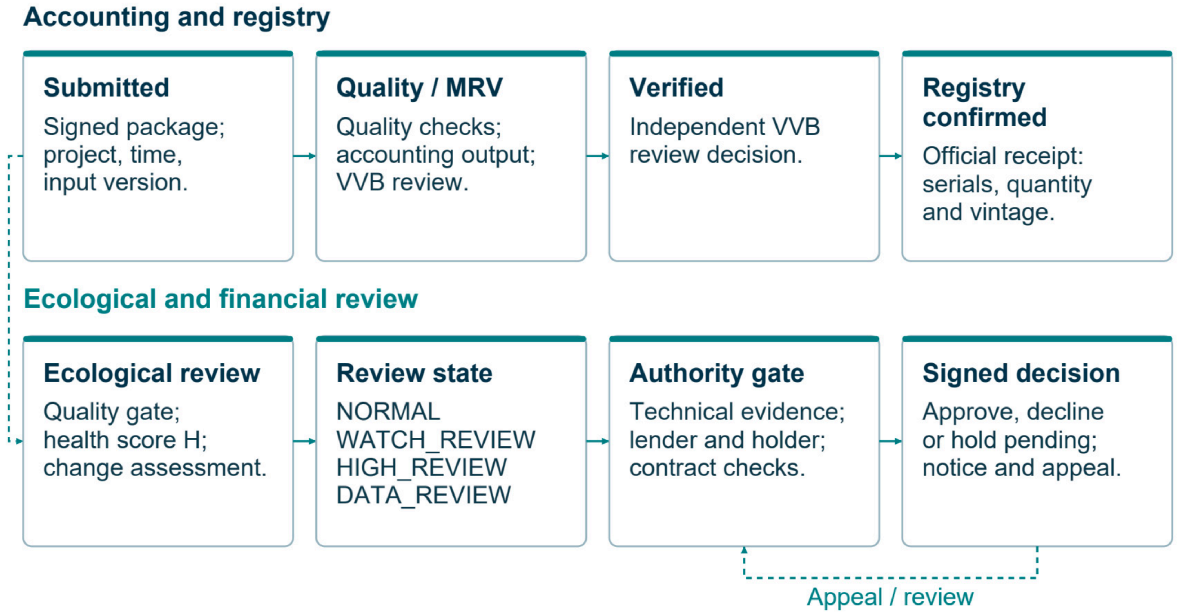

Figure 3. Conceptual business process, review states, and authorised decision points for blockchain-enabled blue carbon finance. Solid arrows indicate the main process sequence; dashed arrows show links between the workflows and the appeal/review feedback path.

Project registration is the starting point of the workflow. The project proponent submits a project design document, boundary, ecosystem type, selected methodology, and supporting evidence through the application layer. The system can store a document hash and defined metadata on-chain while retaining the source document under the stated off-chain access and retention policy. Registration should require the authorised review and signature pathway defined by programme rules. The resulting record identifies the project, methodology version, evidence references, signatory set, and effective time.

The second stage is ecological monitoring data collection and controlled submission. Monitoring devices, satellite products, and field observations may generate raw data such as water temperature, salinity, vegetation coverage, and carbon-accumulation indicators. Authorised oracle services submit signed data packages with time, location,

source, calibration or quality metadata, and version identifiers. The ledger can record a lightweight commitment containing the data-package hash, time window, and project ID. This record supports later integrity and provenance checks. Independent MRV procedures remain necessary to assess measurement accuracy, completeness, representativeness, and ecological interpretation.

The third stage is methodology-governed carbon accounting. After authorised data submissions have passed declared quality checks, the accounting module uses the applicable methodology version to calculate eligible baseline, project, leakage, uncertainty, and permanence terms. Any optional module, including a fire-reduction component, is used only when allowed by that methodology. The module records the approved input version, parameters, calculation output, report hash, and the status awaiting MRV review. Accredited MRV review supplies the assessment of ecological and methodological validity.

The fourth stage is MRV review. The workflow module checks deterministic records such as signature validity, declared data completeness, version consistency, and linkage between committed hashes and submitted files. An accredited MRV body and other authorised parties assess methodology compliance, boundary plausibility, additionality evidence, and any issue requiring expert judgement. The final decision, evidence references, signature set, exception status, and effective date are recorded on-chain. The workflow links the independent professional verification decision to its evidence and effective date.

The fifth stage concerns carbon credit entitlement and trading. Following an authorised MRV decision and the applicable registry rules, the entitlement module can record the quantity, vintage, ownership, verification identifier, ecological-data version, and status of eligible credits. Transfer, pledge, and retirement functions should enforce the defined asset-state rules and preserve the records needed to prevent duplicate issuance, double pledging, or duplicate retirement. Any reversal, replacement, or cancellation process must follow the applicable programme and contractual rules.

The sixth stage is ecological–financial risk review and pledge financing. A credit holder may submit a pledge application identifying eligible credits. The risk-coupling module can generate a governed risk signal from the latest approved ecological-data version, accounting status, and other validated financial risk inputs. The financing module then records authorised lending decisions and locks the pledged credits according to the applicable contract. Ecological changes may prompt a review, notice, or proposed adjustment. Any collateral call, transfer restriction, or liquidation requires the defined legal, contractual, and authorised decision pathway.

The seventh stage covers repayment, retirement, and evidence preservation. After an authorised repayment or retirement event, the relevant module updates the credit state and records the signed supporting evidence. The evidence-preservation function links project registration, monitoring commitments, accounting and MRV decisions, ownership events, parameter changes, alerts, and authorised responses through a time-sequenced audit trail. The evidentiary effect of these records remains subject to jurisdiction-specific law, registry rules, and the integrity of the underlying off-chain evidence.

5. Discussion

This paper proposes a conceptual architecture for full-lifecycle blue carbon finance. Its potential contribution is to make the interfaces among data provenance, ecological-data versioning, MRV workflow, credit-state management, and financial risk review more explicit. Cross-border use follows the institutional authorisation, accounting and reporting requirements for transfers under Article 6.2 of the Paris Agreement. Operational deployment would require validated accounting methodologies, registry interoperability, legal recognition, independent MRV, a security model, and evidence on cost and performance.

Hybrid storage and asynchronous signature collection are design options whose practical benefits should be tested against realistic workloads and governance constraints.

The transition from a conceptual framework to an operational ecosystem raises legal and governance questions. The status of digital signatures, on-chain records, smart contract outputs, and oracle-fed data differs across jurisdictions. Regulatory sandboxes may offer a controlled setting in which financial and environmental authorities can test specific workflow components, define accountability, and assess legal enforceability before deployment.

Regulatory acceptance also depends on oracle integrity and comparable ecological metrics. Multi-source submissions combine with calibrated instruments, independent validation and standardised accounting protocols. Observed salt-marsh carbon losses reinforce the need for spatially and temporally resolved monitoring [67]. Interoperable data formats, methodology representations, and registry interfaces should be developed and tested with relevant standards bodies. Environmental sensor and maritime-adoption studies also identify infrastructure, coordination and governance costs that require evaluation in this setting [68,69].

The architectural and functional design provides a specification for implementation and evaluation. The ecological–financial interface uses configurable indicators and review thresholds. Future work should calibrate and validate these indicators, propagate uncertainty, and assess credit-price, liquidity and legal conditions for an identified project. Prototype implementation, security testing and pilot studies can compare the workflow with conventional MRV, registry and static-risk processes. Evaluation should report latency, scalability, sensor and storage costs, node maintenance, compliance effort and financial outcomes against an explicit baseline.

6. Conclusions

This study proposes a conceptual blockchain architecture for blue carbon finance. It defines a hybrid storage design, a multi-party signature approval workflow, and grouped contract modules for recording authorised decisions across the blue carbon finance lifecycle.

The central proposed contribution is a governance interface that links versioned ecological information to methodology-governed accounting, credit-state management, and authorised financial risk review. The defined review states and actor-specific approvals make this interface explicit and testable while preserving accredited MRV, registry and contractual authority.

Large-scale deployment would require legal recognition of relevant records, methodology-specific accounting, independent MRV, oracle security, privacy and access controls, registry interoperability, and formal evaluation of the signature workflow. Future research should develop and test a prototype using a clearly defined blue carbon project type and methodology. It should then evaluate ecological-data quality, accounting reproducibility, security, cost, latency, and financial risk outcomes against appropriate baselines. The present paper provides the decision structure and evidence interfaces needed for that evaluation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182111290/s1, Table S1: Executed synthetic scenarios; Table S2: Required authority and permitted transitions; Table S3: Descriptive comparison of reported functions and source-defined roles; Table S4: Execution record.

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References

1. Deng, Y.; Liu, Y.; Pratap, A. Climate Change Adaptation: Competing Framings of Security and Development. *J. Isl. Mar. Stud.* **2026**, *5*, 110040. [CrossRef]
2. Deng, Y.; Zhang, H.; Pratap, A.; Failou, B.; Hussain, A.; Putri, H.M. Integrating Climate Change into Global Ocean Governance: The ITLOS Advisory Opinion on the Specific Obligations of State Parties to the United Nations Convention on the Law of the Sea. *J. Isl. Mar. Stud.* **2024**, *1*, 110011. [CrossRef]
3. Feng, C.; Ye, G.; Zeng, J.; Zeng, J.; Jiang, Q.; He, L.; Zhang, Y.; Xu, Z. Sustainably developing global blue carbon for climate change mitigation and economic benefits through international cooperation. *Nat. Commun.* **2023**, *14*, 6144. [CrossRef] [PubMed]
4. Macreadie, P.I.; Costa, M.D.P.; Atwood, T.B.; Friess, D.A.; Kelleway, J.J.; Kennedy, H.; Lovelock, C.E.; Serrano, O.; Duarte, C.M. Blue carbon as a natural climate solution. *Nat. Rev. Earth Environ.* **2021**, *2*, 826–839. [CrossRef]
5. Bertram, C.; Quaas, M.; Reusch, T.B.H.; Vafeidis, A.T.; Wolff, C.; Rickels, W. The blue carbon wealth of nations. *Nat. Clim. Change* **2021**, *11*, 704–709. Correction in *Nat. Clim. Change* **2021**, *11*, 886. [CrossRef]
6. Farahmand, S.; Hilmi, N.; Duarte, C.M. The rise and flows of blue carbon credits advance global climate and biodiversity goals. *npj Ocean Sustain.* **2025**, *4*, 39. [CrossRef]
7. Vanderklift, M.A.; Marcos-Martinez, R.; Butler, J.R.A.; Coleman, M.; Lawrence, A.; Prislan, H.; Steven, A.D.L.; Thomas, S. Constraints and opportunities for market-based finance for the restoration and protection of blue carbon ecosystems. *Mar. Policy* **2019**, *107*, 103429. [CrossRef]
8. Kwan, V.; Friess, D.A.; Sarira, T.V.; Zeng, Y. Permanence risks limit blue carbon financing strategies to safeguard Southeast Asian mangroves. *Commun. Earth Environ.* **2025**, *6*, 57. [CrossRef]
9. Wylie, L.; Sutton-Grier, A.E.; Moore, A. Keys to successful blue carbon projects: Lessons learned from global case studies. *Mar. Policy* **2016**, *65*, 76–84. [CrossRef]
10. Brook, T.; Lutes, M.; Heaps, L.; Walmsley, S.; Randone, M.; Merriman, P. *Responsible Finance for Blue Carbon Ecosystems*; WWF International: Gland, Switzerland, 2023. Available online: https://wwfint.awsassets.panda.org/downloads/wwf_responsible-finance-for-blue-carbon-ecosystems.pdf (accessed on 1 June 2026).
11. Li, P.; Liu, D. How blue carbon financing can sustain blue carbon ecosystems protection and restoration: A proposed conceptual framework for the blue carbon financing mechanism. *Ocean Coast. Manag.* **2025**, *265*, 107644. [CrossRef]
12. European Commission. *Communication from the Commission to the European Parliament and the Council: Sustainable Carbon Cycles*; COM(2021) 800 final; European Commission: Brussels, Belgium, 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0800 (accessed on 1 June 2026).
13. European Parliament and Council of the European Union. Regulation (EU) 2023/839 amending Regulation (EU) 2018/841 and Regulation (EU) 2018/1999. *Off. J. Eur. Union* **2023**, *L 107*, 1–28. Available online: https://eur-lex.europa.eu/eli/reg/2023/839/oj/eng (accessed on 1 June 2026).
14. Verra. VCS Program Details. Applicable Standard, Registration and Issuance Process and Effective-Date Documents. Available online: https://verra.org/programs/verified-carbon-standard/vcs-program-details/ (accessed on 26 October 2026).
15. UNFCCC. Article 6.2 Cooperative Approaches. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/article-6/article-62 (accessed on 26 October 2026).
16. Herr, D.; von Unger, M.; Laffoley, D.; McGivern, A. Pathways for implementation of blue carbon initiatives. *Aquat. Conserv.* **2017**, *27*, 116–129. [CrossRef]
17. Liu, J.; Failler, P.; Ramrattan, D. Blue carbon accounting to monitor coastal blue carbon ecosystems. *J. Environ. Manag.* **2024**, *352*, 120008. [CrossRef] [PubMed]

18. Yaseen, M.; Khan, W.R.; Li, P.; Khalid, F.; Ahmed, U.; Solangi, K.A.; Li, L.; Gul, M.; Bahadur, S.; Sultan, H.; et al. Forest blue carbon sink accounting: Methodological advancements and uncertainty analysis. *J. For. Res.* **2026**, *37*, 53. [CrossRef]
19. Zhou, Y.; Gao, T.; Bu, W.; Wang, Q.; Ran, S. Blockchain technology development, green finance, and urban public transportation service level. *Financ. Res. Lett.* **2025**, *86*, 108850. [CrossRef]
20. Sun, L. Blockchain, supply chain finance collaboration, and the ESG performance of cultural and tourism enterprises. *Int. Rev. Econ. Finance* **2026**, *108*, 105306. [CrossRef]
21. Pramanick, S.; Dey, S.K.; Kundu, K.; Das, P. Impact of blockchain on supply chain finance system considering information transaction costs. *Int. J. Prod. Econ.* **2026**, *301*, 110125. [CrossRef]
22. Guo, P.; Feng, G.; Wang, K.; Zhou, X.; Liu, Q. Analysis of blockchain technology implementing and financing provision strategies in contract farming supply chains. *Transp. Res. Part E Logist. Transp. Rev.* **2025**, *203*, 104385. [CrossRef]
23. He, Y.; Wang, Y.; Xie, S. Identification of risk factors and pathways of mangrove carbon sink projects: From perspective of supply. *Reg. Stud. Mar. Sci.* **2025**, *89*, 104345. [CrossRef]
24. Xu, S.; Liu, S.; Liu, Y. From case study to general principle: An analysis of the development mechanism and policy optimization of mangrove carbon sinks. *J. Clean. Prod.* **2024**, *473*, 143537. [CrossRef]
25. Ji, F. Construction of carbon asset management accounting system under blockchain embedding. *Financ. Account. Mon.* **2023**, *44*, 66–71. (In Chinese)
26. Bi, T.; Xu, N. Can blockchain technology reduce supply chain finance risk? The mediating role of information transparency. *Financ. Res. Lett.* **2026**, *88*, 109137. [CrossRef]
27. Luna, M.; Fernandez-Vazquez, S.; Tereñes Castelao, E.; Arias Fernández, Á. A blockchain-based approach to the challenges of EU's environmental policy compliance in aquaculture: From traceability to fraud prevention. *Mar. Policy* **2024**, *159*, 105892. [CrossRef]
28. Guan, Z.; Tian, X.; Kong, Y. Research on ecological value realization path of Xiongan new area based on blockchain technology. *J. Hebei Univ. Econ. Bus.* **2019**, *40*, 77–86. (In Chinese)
29. Sun, R.; Yan, J.; He, D.; Wang, X. Evolutionary game analysis of blockchain preventing forestry carbon sink projects development risks. *Soft Sci.* **2024**, *38*, 90–100. (In Chinese)
30. He, Y.; Dong, J.; Jiang, C.; Chen, B.; Zhang, S. Blockchain's impact on operation and finance decision: Theoretical examinations across blockchain enabled inventory asset-based finance. *Comput. Ind. Eng.* **2025**, *210*, 111491. [CrossRef]
31. Zhou, L.; Zhang, S.; Hou, F.; Zhang, L. Construction of carbon trading pattern based on blockchain. *Sci. Soil Water Conserv. China* **2020**, *18*, 139–145. (In Chinese)
32. Gholizadeh, Y. Optimizing EU carbon footprint tracking: A low-energy blockchain approach with Proof of Elapsed Time. *J. Environ. Manag.* **2026**, *401*, 128955. [CrossRef] [PubMed]
33. Yang, T.; Ma, C.; Mi, X.; Li, H.; Chen, D. Blockchain-embedded carbon emission allowance pledge financing: Resolving maturity mismatch with machine trust and collateral flexibility. *Int. J. Prod. Econ.* **2026**, *296*, 109947. [CrossRef]
34. Friess, D.A.; Howard, J.; Huxham, M.; Macreadie, P.I.; Ross, F. Capitalizing on the global financial interest in blue carbon. *PLoS Clim.* **2022**, *1*, e0000061. [CrossRef]
35. Zheng, Y.; Lu, W.; Wang, H.; Tao, Y.; Liu, Z.; Ai, Y. Embedding ecosystem-based adaptive management in blue carbon markets: A conceptual framework and operational roadmap for China. *Front. Mar. Sci.* **2026**, *12*, 1702500. [CrossRef]
36. Shiiba, N.; Wu, H.H.; Huang, M.C.; Tanaka, H. How blue financing can sustain ocean conservation and development: A proposed conceptual framework for blue financing mechanism. *Mar. Policy* **2022**, *139*, 104575. [CrossRef]
37. Kuwae, T.; Watanabe, A.; Yoshihara, S.; Suehiro, F.; Sugimura, Y. Implementation of blue carbon offset crediting for seagrass meadows, macroalgal beds, and macroalgae farming in Japan. *Mar. Policy* **2022**, *138*, 104996. [CrossRef]
38. Wang, J.; Lian, X. The impact of blue finance on sustainable development in marine ranching: Exploring multiple pathway. *Res. Int. Bus. Finance* **2026**, *83*, 103259. Correction in *Res. Intern. Business Finance* **2026**, *83*, 103259. [CrossRef]
39. Ye, J.; Huang, X.; Zhou, C.; Jiang, X. Blockchain-enabled maritime financial ecosystems: Evolutionary game analysis of financing efficiency and trust mechanisms. *Ocean Coast. Manag.* **2026**, *276*, 108136. [CrossRef]
40. Wei, J.; Yao, Z.; Ma, S.; Wang, C.; Guo, S.; Zhu, Z.; Si, X. Review of blockchain technology applications in carbon emission trading system. *J. Comput. Appl.* **2025**, *45*, 3872–3880. (In Chinese)
41. Chen, Z.; Zhu, J.; Liu, Y.; Dong, Z.; Xu, Y. A review of the carbon trading market with large-scale user participation based on blockchain. *Renew. Sustain. Energy Rev.* **2026**, *227*, 116475. [CrossRef]
42. Wang, Y.; Xie, E.; Sun, Y. Blockchain technology in sales link under the background of business-finance integration. *Results Eng.* **2026**, *30*, 111104. [CrossRef]
43. Merlo, A.L.C.; Mendonça, D.S.; Santos, J.; Carvalho, S.T.; Guerra, R.; Brandão, D. Blockchain for the carbon market: A literature review. *Discov. Environ.* **2025**, *3*, 68. [CrossRef]

44. Khan, N.; Tahmid, A.; Adar, A.M.; Junayed Hossain, M.; Alam, S.A. A comprehensive hierarchical review of blockchain technology in revolutionizing carbon emission trading system. In *Proceedings of the 2025 IEEE 23rd Student Conference on Research and Development (SCOReD)*; IEEE: Piscataway, NJ, USA, 2025; pp. 1–6.
45. Khan, N.; Tahmid, A.; Adar, A.M. A Comprehensive Hierarchical Review of Blockchain Technology in Revolutionizing Carbon Emission Trading System. Bachelor's Thesis, Independent University, Dhaka, Bangladesh, August 2025. Available online: https://www.ar.iub.edu.bd/handle/11348/1039 (accessed on 27 October 2026).
46. Abiodun, T.P.; Nwulu, N.I.; Olukanmi, P.O. Application of blockchain technology in carbon trading market: A systematic review. *IEEE Access* **2025**, *13*, 5446–5470. [CrossRef]
47. Song, Y.; Wu, H. Evolutionary game analysis of forestry carbon sink trading model under blockchain technology. *Heliyon* **2023**, *9*, e22706. [CrossRef] [PubMed]
48. Dong, Y.; Wu, J. Information and communications technologies for carbon sinks from economics and engineering perspectives. *Digit. Commun. Netw.* **2026**, *12*, 1501–1513. [CrossRef]
49. Zhao, C.; Sun, J.; Gong, Y.; Li, Z.; Zhou, P. Research on the blue carbon trading market system under blockchain technology. *Energies* **2022**, *15*, 3134. [CrossRef]
50. Wahsheh, H.A.M. Securing blue carbon accounting: A cryptographic framework for coastal ecosystem monitoring. *Int. J. Adv. Comput. Sci. Appl.* **2026**, *17*, 700–707. [CrossRef]
51. Verra. Verra Stakeholder Update Webinar October 2025 Recap. 2025. Available online: https://verra.org/verra-stakeholder-update-webinar-october-2025-recap/ (accessed on 27 October 2026).
52. Toucan. Puro Carbon Bridge. Available online: https://docs.toucan.earth/toucan/carbon-bridge/puro-carbon-bridge (accessed on 27 October 2026).
53. KlimaDAO. Retirement. Available online: https://docs.klimadao.finance/developers/contracts/retirement (accessed on 27 October 2026).
54. Verra. Verra Addresses Crypto Instruments and Tokens. 2022. Available online: https://verra.org/verra-addresses-crypto-instruments-and-tokens/ (accessed on 27 October 2026).
55. Toucan. FAQ for transition to Open Source. Available online: https://docs.toucan.earth/resources/frequently-asked-questions/faq-for-transition-to-open-source (accessed on 27 October 2026).
56. IUCN. *Manual for the Creation of Blue Carbon Projects in Europe and the Mediterranean*; Otero, M., Ed.; IUCN Centre for Mediterranean Cooperation: Malaga, Spain, 2021. Available online: https://iucn.org/resources/file/manual-creation-blue-carbon-projects-europe-and-mediterranean (accessed on 1 June 2026).
57. Houston, A.; Kennedy, H.; Austin, W.E.N. Additionality in blue carbon ecosystems: Recommendations for a universally applicable accounting methodology. *Glob. Change Biol.* **2024**, *30*, e17559. [CrossRef] [PubMed]
58. Mengis, N.; Paul, A.; Fernández-Méndez, M. Counting (on) blue carbon—Challenges and ways forward for carbon accounting of ecosystem-based carbon removal in marine environments. *PLoS Clim.* **2023**, *2*, e0000148. [CrossRef]
59. Verra. VM0033 Methodology for Tidal Wetland and Seagrass Restoration. Version 2.1. 2023. Available online: https://verra.org/documents/vm0033-methodology-for-tidal-wetland-and-seagrass-restoration-v2-1/ (accessed on 26 October 2026).
60. Verra. VMD0052 Demonstration of Additionality of Tidal Wetland Restoration and Conservation Project Activities (ADD-AM). Version 2.0. 2021. Available online: https://verra.org/wp-content/uploads/imported/methodologies/VMD0052-Demonstration-of-additionality-of-tidal-wetland-restoration-and-conservation-project-activities-ADD-AM-v2.0.pdf (accessed on 26 October 2026).
61. Verra. Procedure for Applying the AFOLU Non-Permanence Risk Tool. Version 5.0. 2025. Available online: https://verra.org/documents/procedure-for-applying-the-afolu-non-permanence-risk-tool-v5-0/ (accessed on 26 October 2026).
62. Hyperledger Fabric. The Ordering Service. Release 2.5. Available online: https://hyperledger-fabric.readthedocs.io/en/release-2.5/orderer/ordering_service.html (accessed on 26 October 2026).
63. Hyperledger Fabric. Endorsement Policies. Release 2.5. Available online: https://hyperledger-fabric.readthedocs.io/en/release-2.5/endorsement-policies.html (accessed on 26 October 2026).
64. Han, Z.; Ding, T.; Mu, C.; Yao, Y.; Luo, J.; Shen, X. Asynchronous consensus blockchain-based method and smart contract for corporate and personal carbon accounting. *Proc. CSEE* **2024**, *44*, 66–82. (In Chinese)
65. Yu, J.; Zhang, X.; Wang, J.; Zhang, Y.; Shi, Y.; Su, L.; Zeng, L. Robust and trustworthy data sharing framework leveraging on-chain and off-chain collaboration. *Comput. Mater. Contin.* **2024**, *78*, 2159–2179. [CrossRef]
66. Zhang, J.; Cai, K.; Zhao, Q. Warehouse receipt pledge financing using blockchain data asset. *Int. Rev. Financ. Anal.* **2025**, *102*, 104104. [CrossRef]
67. Zheng, Y.; Jiang, Q.; He, Q.; Xiao, X.; Macreadie, P.I.; Xu, X.; Nie, M.; Wu, J.; Ye, G.; Wu, J.; et al. Global blue carbon losses from salt marshes exceed restoration gains. *Nat. Commun.* **2026**, *17*, 3744. [CrossRef] [PubMed]

68. Fiegenbaum, H.; Azegele, B.; Seider, S. Decentralized internet-of-things networks for environmental data pipelines: Opportunities and challenges in a community-based urban green space restoration project in Nairobi, Kenya. *Front. Blockchain* **2026**, *8*, 1626695. [CrossRef]
69. Nguyen, S.; Chen, P.S.-L.; Du, Y. Blockchain adoption in container shipping: An empirical study on barriers, approaches, and recommendations. *Mar. Policy* **2023**, *155*, 105724. [CrossRef]

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