BODHIVRUKSHA JOURNAL OF DIVERSE DISCIPLINE
E-ISSN : 3139-1486
An Open Access, Peer-Reviewed, Multidisciplinary Scholarly Journal
Bi-monthly | Multilingual (English, Hindi, Marathi) | Academic Research
@ Volume 2, Issue 5 (September-October 2026) (Special Issue 1) ISSN: 3139-1486 (Online)

BLOCKCHAIN-POWERED AGRICULTURAL CARBON CREDIT MARKETPLACE: *A Verifier-Attested Architecture for Smallholder Credit Generation, Buffering, and Trading*

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Abstract

Agriculture has the potential to deliver substantial amounts of verified carbon removals, but smallholders rarely participate: costs of certification are fixed per project, evidence of soil carbon is challenging to elicit and verify, and tokenized-credit markets to date are thin and fragmented. This paper describes a blockchain-based marketplace where agricultural credits are both issued and exchanged within a unified platform to ensure supply chain integrity. The design involves farmer-side evidence capture, digitalization with conservative uncertainty discounts, a *k*-of-*n* quorum of accredited verifiers, batch-minted tokens that encode quality information, a buffer pool for reversals, and an escrowed order-book market that settles on-chain and delists in a national registry. As the implementation of the system has yet to happen, the attributes of the system are assessed in terms of mathematical models in which parameters are determined beforehand. Through Merkle batching, transaction costs decrease from 24,000 to 46 gas units for every record at the batch size of 1,000. A quorum consisting of 5 out of 9 members results in a reduction of the risk of accepting a false proof by 100 times to 0.09% if 10% of the validators are compromised. Detection of spatial overlaps allows for the identification of parcels that are being enrolled multiple times with respect to the GPS discrepancies below 5 meters with recall worth at least 99.4%. The aggregated project would require 446 ha under the assumption of baseline conditions instead of 1,713 ha to achieve cost-effectiveness, while the buffer cost percentages of 15 to 30% could be required depending on the level of risks. The results are entirely hypothetical and should be interpreted as scenarios rather than measurements in any deployed system.

Keywords: Agricultural carbon credits, blockchain, digital MRV, smart contracts, smallholder farmers, tokenization.

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I. Introduction

Agriculture, forestry, and other land use (AFOLU) accounts for roughly 13–21% of global anthropogenic greenhouse-gas (GHG) emissions on average over 2010–2019, and about 22% in 2019, according to the IPCC's sixth assessment [1]. Same land base can also remove carbon, via practices like agroforestry, residue management, and improved soil management. Carbon credits seek to channel that removal potential into income, but the farmers who manage most of the world's cropland are not the ones who capture it.

India provides an example; in the 2015–16 Agriculture Census, small and marginal holdings accounted for about 86% of all operational holdings, but operated only about 47% of the cropped area, and the average holding was about 1.08 ha [2]. Fig. 1(c) summarizes this structure. Single hectare-scale farms cannot carry the fixed cost of validating and verifying a carbon project, so any credible route to market aggregates many holdings under one project, and aggregation itself has trust implications: who owns the land, consented, is paid, and whether the same field was enrolled twice.

Reviews report gains in transparency and fraud resistance, but unresolved interoperability and governance problems [3]. Empirical record of tokenized trading is modest: on the AirCarbon Exchange, about 3.8 $MtCO_2e$ were tokenized over 2021–22, about 2.8 Mt were retired, and secondary-market turnover was only $21.2 million, with 36 minting wallets and 78 trading wallets [4]. KlimaDAO's treasury was dominated by a single pooled token (87.16% of its value in May 2024), and reported that its on-chain activity has been reported to fade over time [5]. Plotted in Fig. 1(a)–(b), these figures suggest that recording credits on a ledger is the easy part: the hard parts are what gets minted, how its quality is described, and how a farmer's evidence is trusted.

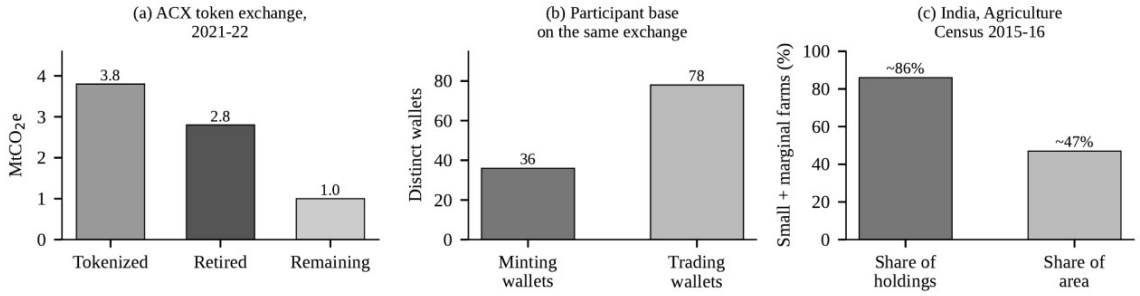


Fig. 1. Published statistics that motivate the design. (a), (b) Activity on the AirCarbon Exchange token market, 2021–22 [4]. (c) Structure of Indian landholdings: small and marginal farms hold about 86% of holdings but operate about 47% of the area (rounded values from the 2015–16 Agriculture Census [2]).

Research gap. Most proposals in the literature that consider placing carbon credits on a blockchain relate to industrial or corporate carbon exchanges. The few agricultural proposals either report marketing or provenance pilot schemes or toy implementations of one or more of the mechanisms described in this paper. In the survey of related work (Section II), we find no prior work that jointly considers smallholder-centric measurement, verifier-attested issuance, reversal buffering, and

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differential trading of carbon credits as a system, nor any analysis of the costs and security implications of such a pipeline. We make no claim about the absence of such work elsewhere; this is a finding only about the surveyed set.

Contributions. This paper makes five contributions:

1) An architecture in which credits are issued and exchanged on a platform, but may only be minted after independent attestation and a registry reference, thereby resisting unilaterally issued credits on the platform.

2) Evidence-integrity mechanisms adapted to smallholders, including batched hash anchoring of field evidence, spatial overlap screening of registered plots, and an issuance rule that accounts for measurement uncertainty.

3) Revocation-and-valuation model that includes a pool of tokens amenable to temporary retirement plus tokens that keep information regarding validity, sector of application, area of use, and indirect cost, instead of accumulating within the same pool.

4) This refers to a danger model that contains the mapping of threats to the elements of the system.

5) The last item is devoted to a replication investigation encompassing costs of smart contracts, approval of the quorum, detection of double spending cases, economics of small owners, and calculation of buffer sizes, and made available through fixed random number generators.

The rest of the paper is organized as follows. Section II reviews related work and states the gap. Section III gives requirements and the threat model. Section IV presents the system. Section V reports the evaluation, Section VI discusses limitations, and Section VII concludes.

II. Background and Related Work

A. Agricultural Carbon Credits and Their Measurement Problem

A carbon credit is one metric ton of CO_2 equivalent that has been avoided, reduced, or eliminated. In agriculture, the problem lies in the proof of the actual ton. This is because soil carbon changes slowly and may differ quite considerably even over short distances, carbon removal can be undone by tillage, fire or changes in land use, and the resulting environmental benefit must be additional to what would have happened anyway. A recent analysis of the agriculture sector in India recognized measurement and verification of the process as a major issue facing smallholders. Some of the barriers identified include cloud cover being an obstacle to optical satellite monitoring in humid regions; communal land tenure making it hard to commit; and transaction costs absorbing most of the potential gains [6]. A study carried out on the carbon credit schemes in Canada reinforced the same idea but from the economic standpoint, as the participation of farmers in carbon offset programs remained low due to the offset prices not being able to cover the costs [7]. Early Indian discussions of carbon trading focused on clean-development projects in the energy sector, with farmers only as a prospect for selling credits [8].

B. Blockchain Designs and Evidence for Carbon Markets

Prior research on blockchain for carbon markets falls into four categories. A literature review covering 2022 to early 2024 finds that smart contracts can automate verification and settlement, and that

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platform interoperability and governance remain open [3]. A technical survey of tokenization compares the mechanisms used by Toucan, Flowcarbon, MOSS, Nori, and others, shows that tokenized credits are a heterogeneous family that hinders interoperability, and notes that pooling credits erases quality differences. It also describes Nori, the one agricultural precedent, which issues credits from cropland under a multi-year storage commitment backed by an insurance reserve [9].

The second category is empirical. Swinkels documents thin trading and concentrated participation on a blockchain exchange [4], and Ballesteros-Rodríguez *et al.* analyse on-chain data for KlimaDAO's tokenized credits [5].

The third category proposes architectures. Golshani and Mankar describe a trading platform in which each credit is a non-fungible token, certifiers are registered on-chain, and an off-chain order book matches orders that settle on-chain [10]. Kim and Huh combine a blockchain with big-data and AI-based anomaly checks and a governance layer for carbon emission rights [11]. Wang and Peng log corporate carbon-trading data on a blockchain and tune contract parameters with an optimization algorithm, evaluated by simulation on a public dataset [12]. Padmavathi *et al.* sketch a blockchain with augmented-reality product visualization for agricultural marketing; its credit counts are simulated values [13].

The fourth category concerns digital MRV. A qualitative review argues that satellite analytics and machine learning can strengthen verification and discusses over-crediting concerns in rice-farming projects [14]. None of these works builds and evaluates an end-to-end issuance pipeline for smallholders.

C. Policy Context in India

India's Carbon Credit Trading Scheme (CCTS) has a compliance mechanism for obligated entities and a voluntary offset mechanism. According to trade publications and market experts, agriculture will be one of the first sectors to use the mechanism, as the methods for obtaining it will be based on those used by other countries by 2025 [15], [16]. The registry is reportedly implemented by the Grid Controller of India and the specific targets that can be achieved by the agriculture sector have been published by the end of 2025 [17]. The risk of double-counting of carbon credits is also mentioned by experts as it is possible to receive credits according to more than one scheme [16]. As the system is still being developed, the platform is not intended to replace the registry but rather connects to it. Statements regarding the registry in this text should be verified against valid documents.

D. Comparison and Gap

Table I assesses the works analyzed in terms of the characteristics essential for agricultural credit producing and trading. It is based on the authors' understanding of each work in question

Table I: Comparison of Related Work (Y = addressed, P = partial or conceptual, N = not addressed)

Work	Focus	Agri.	Digital MRV	Reversal	Trading	Evaluation
[13]	Agricultural marketing with offsets	Y	N	N	P	Demonstration output
[11]	Emission-rights verification and dApp	N	P	N	P	Testbed performance

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Work	Focus	Agri.	Digital MRV	Reversal	Trading	Evaluation
[12]	Corporate trading-data logging	N	N	N	P	Simulation, public data
[10]	Hybrid trading platform	P	N	N	Y	None
[9]	Tokenization survey (incl. Nori)	P	P	P	Y	Survey
[3]	Blockchain in carbon markets	P	P	N	P	Literature review
[14]	AI-enabled digital MRV	P	P	N	P	Qualitative
[4]	Token exchange activity	N	N	N	Y	Empirical, 2021–22
[5]	KlimaDAO tokens	N	N	N	Y	Empirical, on-chain
[6], [7]	Agricultural carbon reviews	Y	P	P	N	Reviews
This work	**Generation and trading on one platform**	**Y**	**Y**	**Y**	**Y**	**Simulation and analysis**

The gap that follows is nuanced. Tokenization and tokenized trading exist as a technical reality [9], [10] but are not accounted in the reviewed papers in terms of the design and evaluation incorporating the evidence of smallholders, verifier attestation, reversal buffering, and quality differentiated trading.

III. Requirements and Threat Model

A. Design Goals

The system is designed against seven goals. G1, accessibility: smallholder farmers must register through a cooperative or organisation with the use of a phone, irrespective of the fact if they possess it or not. G2, evidence integrity: ensure that any modification made afterwards to the evidence submitted can be detected. G3, legitimate issuance: african countries must not issue carbon credits without being independently verified. G4, non-permanence: reversals will be covered from a reserve fund. G5, quality preservation: trading must not erase the differences between vintage, practice, region, or the permanence. G6, cost efficiency: the costs incurred by each farmer on the blockchain should be less than their revenue. G7, regulatory fit: the platform must connect to a national registry and store personal data off the blockchain.

B. Threat Model

It is presumed that the farmers, aggregators, buyers and individual verifiers may act untrustworthy which in turn allows the chain to provide integrity and existence of information that is captured and the trustworthiness of the platform operator for liveness but not for the correctness of the records. Details in Table II provide insight into the risks taken into account and which part is responsible for them. The blockchain provides security of data after it is written but it does not prove that it was honest at the moment of writing. That is why the threat model considers the border between evidence and blockchain (oracle problem discussed by [3]) as the main weakness.

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Table II: Threats and Mitigations

ID	Threat	Mitigation (component)
T1	Duplicacy or overlapping in the enrollment of plots	Spatial overlap verification through IoU threshold, duration and consent verification using unique identifiers (ProjectRegistry)
T2	Fake or modified field proof	Capturing proof using signed, time-stamped and geo-tagged method; hashing method; satellite verification; random field checks (EvidenceAnchor)
T3	Verifier's deceit or collusion	*k*-of-*n* system, random assignment, public testimony and removal of accreditation (AttestationQuorum)
T4	Duplication of claims	Unique batches, stops on export to registry, retirement events repeated in registry (CreditToken, Retirement)
T5	Wash trading and market manipulation	Verified accounts, escrow, crosscheck of self-dealing, watch over auction size and price bands (Marketplace)
T6	Problems in smart contracts (access control, re-entrancy)	Small audited contracts, role separation, pause key, time-locked upgrade (Governance)
T7	Rollback after issuance	Buffer pool, continuous supervision, replacement using buffer (BufferPool, Rollback handler)
T8	Exposure of farmer's name and plot location	Only hashes and coarse cell identifiers on chain; polygons encrypted off chain; used of role-based access

IV. Proposed System

A. Overview and Roles

In Figure 2, the four-layer architecture is illustrated. Entities involved in this architecture include farmers or farmer-producer organizations, aggregators, registered verifiers, buyers, and a registry administrator. Off-chain services involve bulk data collection and calculations: an evidence repository, a digital MRV engine, a spatial overlap index, an order book, and a payment processor. A private or proof-of-stake network hosts the contracts which ensure storing the trust-dependent state. External systems provide national registry, satellite and climate information, and the banking system. The separation follows the hybrid design of keeping order fulfillment and large files off-chain and linking commitments and settlements on-chain [10], [11].

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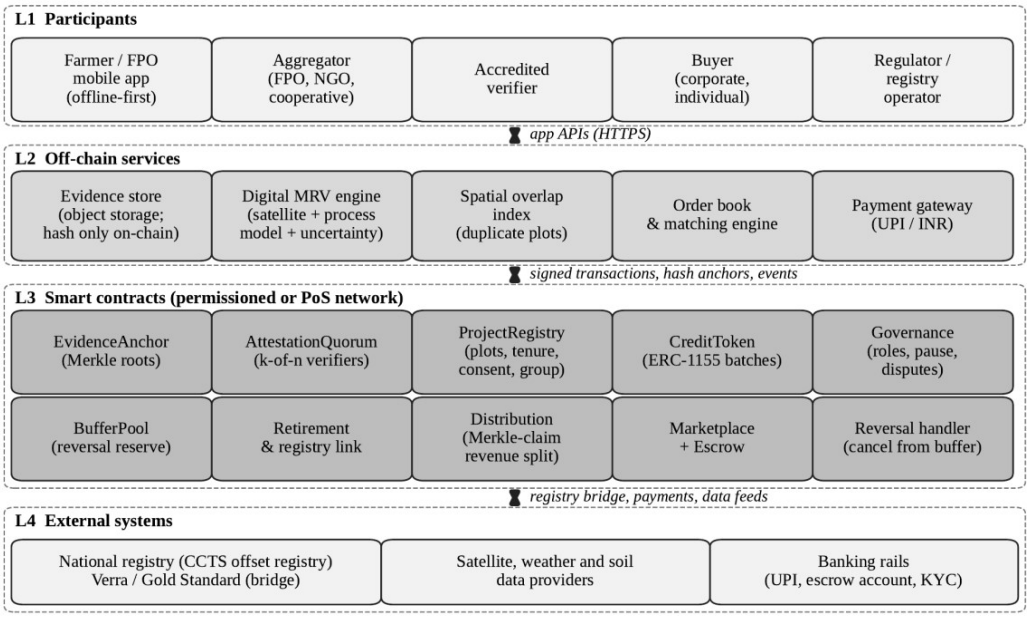


Fig. 2. The proposed marketplace has four-layer construction, where all heavy information and matchmaking remain within off-chain architecture while all commitments, attestations, issuing, buffering, settling, and retiring happen on the chain

B. Credit Unit and Data Model

Credits are produced in groups instead of in one unit per metric ton. A unique identifier is the hash of the project id, vintage, methodology id and permanence dimension. Each group contains meta information such as a technique (for example agroforestry or crop residue management), region cell, vintage year, methodology, verifier set, buffer share and registry link. All units inside a batch are interchangeable and can be divided into a set number of decimal points, therefore one unit will equal to one ton CO_2e and the buyer can buy part of a batch. Different batches cannot be combined into a blended pool. This structure preserves the features of quality that pooled systems lose and allows to have different prices per quality level. (Section V).

C. Credit Lifecycle

Fig. 3 at the onset of the ten-step process involving enrollment to reversal management, the steps mostly bear the load of integrity, and two steps are represented by algorithms

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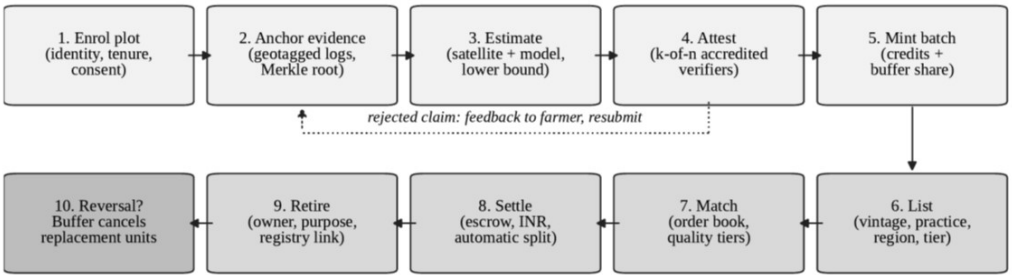


Fig. 3. Credit lifecycle. A claim that is rejected at attestation returns back to the evidences submission.

Enrollment including overlap screening. Prior to the creation of credits, the polygon of the parcel has to be simplified, spatially indexed, and compared to all the approximating polygons. Algorithm 1 recognizes the new parcel if it shares the intersection over union (IoU) of its area with other areas above the threshold τ. [6].

Algorithm 1 Plot enrolment with overlap screening

Require: polygon P, owner u, consent proof c, threshold τ
$P \leftarrow$ NORMALIZE(P)
$C \leftarrow$ SPATIALINDEX.QUERY(BBOX(P))
for each $Q \in C$ **do**
  if IOU(P, Q) $\geq \tau$ **then**
    return REVIEWREQUIRED
  end if
end for
if VERIFYTENURE(u, P, c) fails **then**
  return REJECTED
end if
store encrypted P off-chain; anchor $h = H(P \parallel u \parallel \text{nonce})$ in ProjectRegistry
insert P into the spatial index
return ENROLLED

Attested issuance. It is demonstrated in algorithm 2 that for minting one requires k valid signatures of randomly chosen n accredited verifiers and registry reference. By using a commit-reveal seed to draw the verifier set, the operator cannot choose favorable verifiers.

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Algorithm 2 Attested minting

Require: project j, period t, evidence root r, estimate $(\hat{\Delta}, \hat{\sigma})$, tier
1: compute C by Eq. (??); set $b \leftarrow b$(tier)
2: $d \leftarrow H(j \parallel t \parallel r \parallel C \parallel$ methodology)
3: $V \leftarrow$ SELECTVERIFIERS(n, seed); collect signatures S on d
4: **if** |VALID(S, V)| < k **or** registry reference absent **then**
5: **return** REJECTED
6: **end if**
7: mint batch with $(1 - b)C$ units to project escrow
8: transfer bC units to BufferPool
9: emit MINTED(batchId, d, reference)
10: **return** MINTED

D. Evidence Anchoring and Privacy

Field logs, pictures, and sensor readings are saved off-chain. Each batch of evidence is hashed into Merkle tree with only the root written on-chain, so all information can be later verified against that root. Information on-chain will contain hashes and only approximate cell identifiers; exact polygons and identity will remain encrypted off-chain. Role-specific access is applied (T8). There is a possibility of creating zero-knowledge proof about a non-overlap, but this is not included in the present project.

E. Marketplace, Settlement, and Revenue Split

Sellers offer batch units for sale at a set price. Transactions are facilitated in an off-chain book, while settlement occurs through on-chain escrow. Therefore, escrow and payments are bundled together [10]. Farmers receive their payment in rupees, therefore the payment gateway handles UPI payments. This escrow for the batch is documented in the agreed payout contracts: $f_f + f_a + f_p = 1$. The ability to make payments in compliance with Indian regulations, whether on a public or private blockchain, is dependent on current permissions regarding the relevant technology.

F. Reversal Handling and Retirement

The buffer pool contains units that are retained from all projects. After monitoring or verification happens, the reversal handler cancels equivalent amounts of units in the buffer pool allowing the buyers' claim to remain valid. Similar practices of maintaining insurance reserves are documented in agro tokenized credits [9]. Retirement implies a burn of units on-chain, specifies the beneficiary and its cause, and replicates the process in the national registry; units entered for registry cannot be used again on-chain (T4).

V. Evaluation

A. Scope and Method

Neither field testing nor chain deployment has been conducted, therefore this part does not present the values of any performance measured. It assesses design characteristics through number of analytical models and Monte Carlo simulations. All experiment runs and tests are based on a seed, the relevant parameters are stated in Table III and the source authors have provided codes and raw

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outputs of the experiments for repetition and modification by other parties. Some of the parameters labeled "assumed" indicate the need for calibration in real pilot experience; what is more essential is the overall picture rather than the definite numerical values of obtained results.

The conventional share m = 20% is the upper end of the 10–20% intermediation range reported anecdotally for carbon-credit transactions [4]. The proposed-route values for m, F, and c are design targets, not measurements, and the results below should be read as "what follows if the design achieves these targets".

Table III: Parameters of the Economic and Buffer Models

Symbol	Meaning	Value (sweep)
s	Net removal, tCO_2e/ha/yr	1.5 (0.8–3.0), assumed
p	Credit price, USD/tCO_2e	10 (6–14), assumed
d	Uncertainty discount	15% (5–30%), assumed
b	Buffer withhold	15% (5–30%), assumed
m	Intermediary or platform share	20% conv. / 8% prop. (4–30%)
F	Fixed validation and verification cost per cycle	USD 40k conv. / 20k prop. (10k–80k), assumed
T	Cycle length	5 years
c	Field MRV cost, USD/ha/yr	4 conv. / 1 prop., assumed
$\bar{a}$	Average holding	1.08 ha [2]

B. E1: On-Chain Cost of Evidence Anchoring

Writing one hash per record to contract storage costs a storage slot per record. Writing one Merkle root per batch amortizes a fixed transaction cost over N records. Using Ethereum-style protocol gas constants (21,000 base, 20,000 plus 2,100 for a new cold storage slot, 16 per non-zero calldata byte, and event-log costs), a per-record write costs 23,993 gas, whereas a batch root costs 45,825 gas per transaction:

$$g(N) = \frac{G_{\text{batch}}}{N}, \quad G_{\text{batch}} = 45{,}825 \text{ gas}. \tag{1}$$

Fig. 4 and Table IV show the result. At N = 1,000 the cost falls to about 46 gas per record, a reduction of roughly 520 times. At an illustrative 20 gwei and USD 2,500 per ETH, which are example parameters and not market data, that is about USD 1.20 per record against USD 0.002. Records can still be proven individually against the root off-chain.

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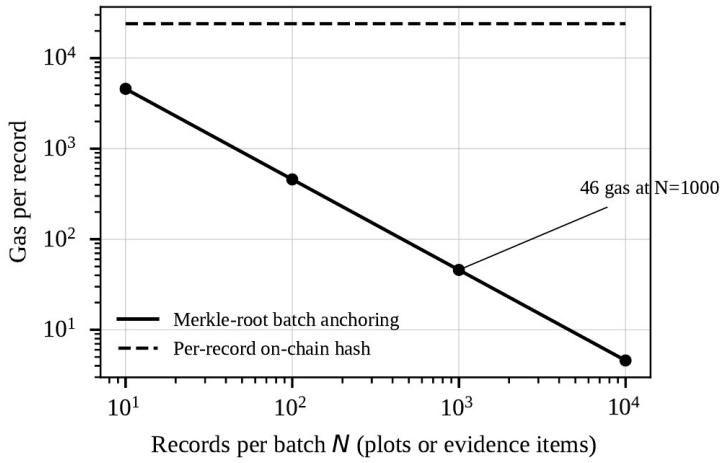


Fig. 4. Gas per record for per-record hashing versus Merkle-root batch anchoring (analytical model).

Table IV: Gas per Record: Per-Record Hash vs. Merkle Batch

N	Per-record	Merkle batch	Reduction
10	23,993	4,583	5×
100	23,993	458	52×
1,000	23,993	46	524×
10,000	23,993	4.6	5,236×

A second comparison concerns tokenized farmer entitlements. Pushing a balance to each farmer costs about 27,100 gas per farmer in this model, whereas letting farmers claim against a Merkle root costs about 44,660 gas per claim. Pushing is cheaper when most farmers claim; claiming wins only if fewer than about 61% claim promptly, or if claims are sponsored on a low-fee network. Since farmer payouts in this design are made in rupees through the payment gateway, on-chain claiming is optional. These figures come from protocol constants and not from a deployed contract, and fees on a permissioned or layer-2 network differ.

C. E2: Security of the Verifier Quorum

Suppose each of the n selected verifiers is corrupt independently with probability p, and a false claim is attested only if at least k of them are corrupt:

$$P_{\text{fail}}(n, k, p) = \sum_{i=k}^{n} \binom{n}{i} p^i (1 - p)^{n-i}. \quad (2)$$

Fig. 5 plots this for five configurations. At $p = 0.10$ a single verifier fails with probability 0.100, a 3-of-2 quorum with 0.028, 5-of-3 with 0.0086, 7-of-4 with 0.0027, and 9-of-5 with 0.0009. At $p = 0.20$ the values are 0.200, 0.104, 0.058, 0.033, and 0.020. A Monte Carlo check with 2×10^6 trials gave 0.00859 for the 5-of-3 case at $p = 0.10$, against the exact 0.00856. The model assumes independent corruption, so collusion among verifiers who share an owner or client is not captured, and random assignment from a large accredited pool is what makes the independence assumption plausible.

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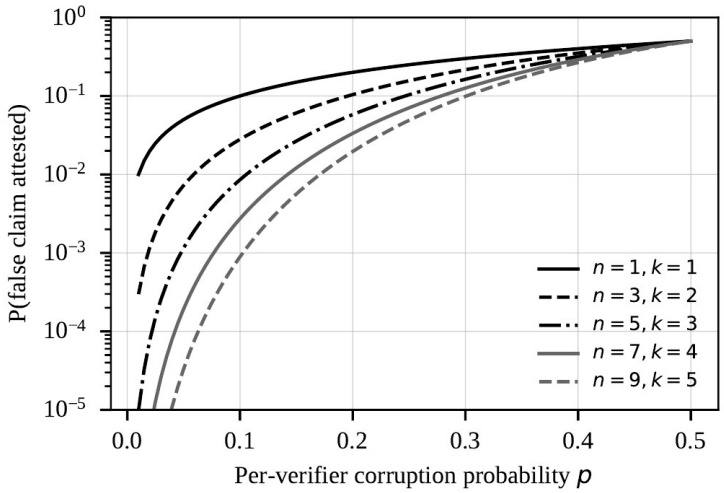


Fig. 5. Probability that a false claim is attested, by quorum size (n, k) and per-verifier corruption probability p (analytical).

D. E3: Duplicate-Plot Detection

We simulated enrolment on a 40×40 tiling of 100 m squares (1,600 one-hectare plots, close to the 1.08 ha average holding) with shared boundaries. Every registered polygon receives independent Gaussian noise of standard deviation σ on each vertex to mimic GPS error. A fraction of 10% of plots (160) is then re-enrolled by an attacker, shifted by up to 15% of the side length and perturbed by new noise. Algorithm 1 screens each re-enrolled polygon against its neighbours. False positives are measured on 600 sampled legitimate plots against their adjacent plots. The seed is fixed.

Fig. 6 shows recall and false-positive rate. With $\tau = 0.5$, recall is 1.00 for noise up to 2 m, 0.994 at 5 m, 0.95 at 10 m, and then falls to 0.46 at 20 m and 0.18 at 30 m, with no false positives. With $\tau = 0.2$, recall is 1.00 up to 10 m, 0.994 at 20 m, and 0.83 at 30 m, but false positives appear at large noise (3.2% at 20 m and 15% at 30 m), because adjacent legitimate plots begin to overlap. The median IoU of an attack plot against the original decreases from 0.75 with low noise to 0.49 with 20 m noise, whereas the 95th percentile of legitimate neighbor IoU increases from 0.006 with 0.5 m noise to 0.19 with 20 m noise. A practical takeaway from this is that the value of τ must be set based on the GPS accuracy of the equipment used to make the capture: a lower threshold is beneficial when noise is low but dangerous when noise is too high, while ambiguous cases should be sent to an actual person rather than be decline automatically. Real parcels are irregular and noise is spatially correlated, so this experiment is a sanity check and not a validation.

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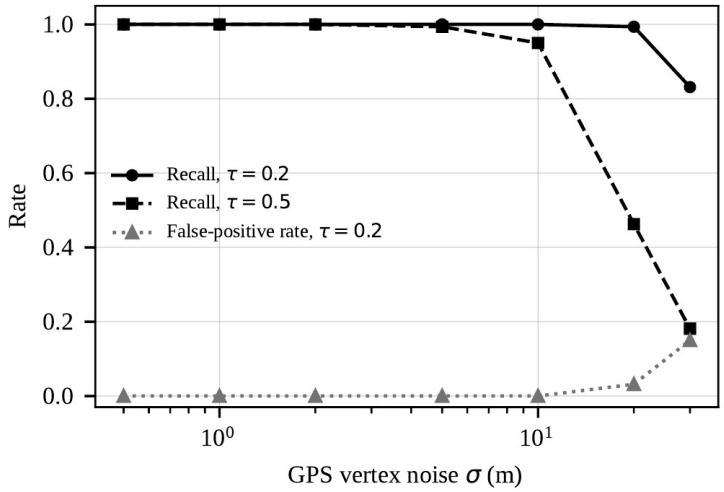


Fig. 6. Duplicate-plot detection: recall at IoU thresholds $\tau = 0.2$ and 0.5, and false-positive rate at $\tau = 0.2$, versus GPS vertex noise (simulation).

E. E4: Smallholder Economics

Net annual farmer income per hectare for a project covering A hectares is modelled as

$$y(A) = s\,p\,(1-d)(1-b)(1-m) - \frac{F}{A\,T} - c, \tag{3}$$

and the break-even area at which $y(A) = 0$ is

$$A^{*} = \frac{F}{T\,[s\,p\,(1-d)(1-b)(1-m) - c]}. \tag{4}$$

Fig. 7(a) plots Eq. (3) for the conventional and proposed parameter sets of Table III. The conventional route breaks even at about 1,713 ha, equivalent to roughly 1,586 farms of average size, whereas the proposed scenario breaks even at about 446 ha, or about 413 farms. At 500 ha the conventional route loses about USD 11.3 per hectare per year while the proposed scenario earns about USD 1.0. At 2,000 ha the figures are USD 0.7 and USD 7.0, and for very large projects the proposed scenario plateaus at about USD 8.8 per hectare per year.

The one-at-a-time sensitivity in Fig. 7(b) shows that the fixed cost F dominates. Varying F from USD 10,000 to 80,000 moves the break-even area from about 223 ha to 1,784 ha. The removal rate s is changed from 0.8 to 3.0, which is from 926 ha to 211 ha, and the price p is modified from USD 6 to 14, and it changes from 803 ha to 309 ha. The role of the intermediary share, buffer, and uncertainty discount is not as serious in comparison with others, as their range is between 394 ha and 607 ha. The sobering result follows: when taking into account the basic parameters the farm measuring 1.08 ha is able to earn USD 9-10 per year as credits at the plateau and USD 29 per year at the corner ($s = 3$, $p = 14$). The income gained from carbon is not promising enough to improve the life of small farmers which is in line with the previously mentioned obstacles to participation in [6], [7]. The platform can

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provide value in terms of enabling aggregation and cutting down on fixed costs, leakage of revenues to intermediaries, and calculating co-benefits via pricing through quality tiers of the service.

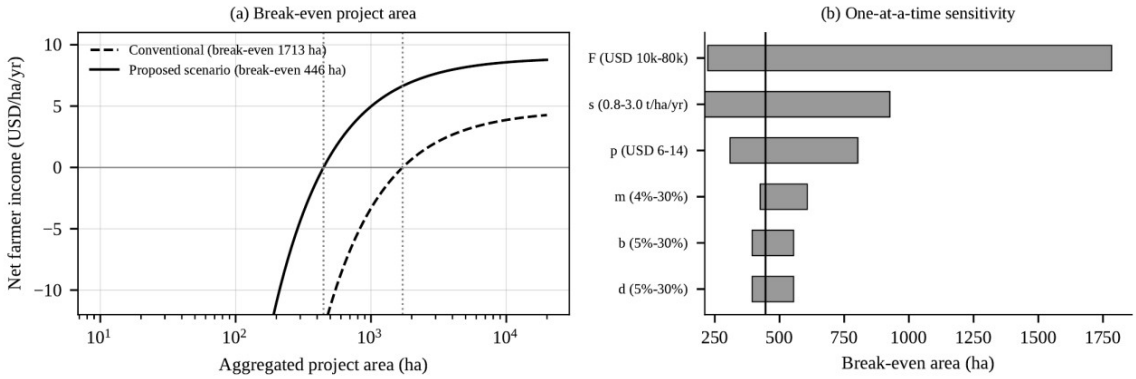


Fig. 7. (a) Net farmer income per hectare against total project size for conventional and recommended variables. (b) One-at-a-time sensitivity of the break-even area in the recommended case (scenario model and not actual data).

F. E5: Sizing the Buffer Pool

For a period of 20 years, we carried out a simulation with a portfolio comprising of 1000 plots. The credit issued per plot each year follows a log-normal distribution with median = 1.5 and log STD = 0.6, with a percentage b of the amount remaining in reserve. Supposedly, every year all the existing plots have a chance q of being reversed and in this case, the plot that has been reversed will no more be eligible for the pool. As a result, in case of reversing any plot, all credits issued will be canceled. It is said that a pool is insolvent when the claims for the year exceed buffer balance. In the correlated variation, there occurs a regional shock with 0.1 probability per year, and the q then multiplies by five during that year. Each of the points involves 3000 trials, so the standard error of the Monte Carlo is about 0.9 percentage points at maximum.

Fig. 8 Shows up the probability of insolvency against b. At q = 1%, given independent reversals, there is certainty of insolvency at $b \leq 5\%$. At b = 10% the probability of insolvency is 0.18 and zero at 15%. For the case of q = 2% it is shown to be 0.93 at 15% and zero at 20%. The inclusion of correlated shocks increases the requirement. At q = 1%, the insolvency probability is 0.82 at 10%, 0.13 at 15%, 0.003 at 20%, and zero at 25%. At q = 2%, the insolvency is 0.99 at 15%, 0.60 at 20%, 0.14 at 25%, and 0.004 at 30%. In this case, correlated hazards require about 5–10% higher liability while a pool spread in uncorrelated conditions would reduce the requirement but won't eliminate it. The reversal percentages can be considered as numbers for placeholders, and the application of the buffer rule requires calibration of the observed reversals before use.

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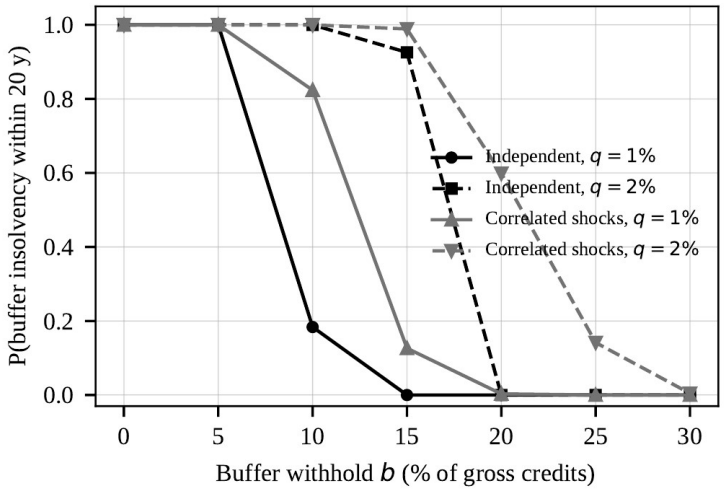


Fig. 8. Probability of buffer insolvency within 20 years versus buffer withhold, for independent and correlated reversal risk at q = 1% and 2% (Monte Carlo, 3,000 trials per point).

VI. Discussion

What the findings indicate. The hypotheses endorse four design strategies. Batching evidence commitments minimizes the cost incurred by the blockchain for every record. Using a small randomly selected quorum dilutes the impact of corrupt verifiers by several times. Spatial screening can identify the re-enrolled plots given that interference is under control. Moreover, the upfront costs of the project rather than the blockchain cost decide about participation of the smallholders, turning aggregation into a must-have rather than an option.

Evidence from operating markets. The low level of transactions registered on tokenized exchanges suggests that the new platform should not be based only on the open market [4], [5]. Having "contracted forward offtake" in place with the buyers who appreciate quality grades gives the new projects protection against price drops; besides, choice of quality-graded batches avoids loss of useful information because of amalgamation [9].

Limitations. There are multiple restrictions involved. To begin, there is no deployment, and thus the gas figures come from constants of the protocol and can differ according to the network used. The idea in the quorum model relies on the assumption of the corruption of independent verifiers. This overlap experiment utilizes synthetic square plots and independent noise. Economic assumptions and buffer parameters are assumed without being validated. Blockchain integrity commences the moment it is written. The process of estimating the amount of carbon present in the soil does not improve the reading that has already been made. Thus, the quality of MRV engine and sampling of verifiers is the highest risk as evidenced by the review of MRV for Indian landowners. Furthermore, the legal status of tokenized credits, rupee settlement, and registry linkage in India are yet to be developed, and consequently, the design retains the registry as the authority and the token as a reflection. Moreover,

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tokenization can also create new risks since it is prone to quality dilution as the effect of pooling comes into play. [5], [9].

Threats to validity. The above simplifications restrict internal validity while external validity is constrained since parameters are not selected from a particular geographic area, type of crops, or farming practices. Moreover, construct validity is reduced because the term "break-even area" merely summarises the wider set of legal and social challenges, namely land ownership and approval [6].

Future work. Some of the future steps involve running a pilot program with the local farmer and producer organisations to understand the rates of removal and reversal including the mistake rates, building a testnet with an independent audit contract, measuring real-time emission and lag, zero-knowledge proofs, and making a legal analysis of Raj.

VII. Conclusion

A blockchain-based market in which agricultural carbon credits are created and traded is provided by this research. However, during the issuance process, users must establish a number of accredited validators without any contribution from the platform. Evidence of agricultural influence is handled in batches, duplicate fields are detected through spatial analysis, uncertainty is removed prior to issuing the credits, and reversals rely on a reserve. Simulation assessments demonstrate significant expenditures on the blockchain for batch processing, stable security against violations, and efficient duplicate detection using low-precision GPS data. A covered project size is dictated by a non-variable check-up cost. Moreover, at reasonable prices, income from carbon credits is not high, thus paving the way to a higher value of the process of combining due to the lower level of leakage and the quality of issued credits. Since simulations were made, a real-life pilot experiment is needed to complete this solution.

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