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Beyond soil carbon credits: integrating greenhouse gas accounting, soil respiration, carbon permanence, and farmer-centred climate governance

Abstract

Agricultural soils are increasingly positioned as both climate-mitigation assets and sources of farmer income. Yet a measured increase in soil organic carbon does not, on its own, establish a durable, additional, and net atmospheric benefit. This qualitative literature review examines the scientific and governance conditions under which soil-carbon interventions create credible climate value, using four linked questions: Is the change real? Will it persist? Is the outcome net of all greenhouse gases? Is the arrangement fair to farmers? It interprets peer-reviewed evidence published during 2020–2026 on carbon-stock dynamics, soil respiration, methane and nitrous oxide, monitoring and verification, ecosystem protection, market integrity, and smallholder participation. The synthesis distinguishes stock enhancement from emission avoidance, temporary storage from fossil-emission neutralization, and individual-field estimates from landscape-level accountability. For tropical agriculture, including Indonesia, peatland hydrology and irrigated-rice methane management often warrant greater immediate attention than uncertain short-contract soil-carbon offsets. The paper proposes an integrated four-gate integrity framework and a farmer–scientist–government monitoring architecture. It recommends differentiated climate claims, long-term public stewardship finance, uncertainty-adjusted measurement, whole-farm safeguards, and equitable benefit sharing. Soil carbon should be rewarded for verifiable soil health, adaptation, avoided degradation, and honestly characterized climate contributions, without automatically presenting every additional tonne as a permanent offset. Operational recommendations include risk-based reversal reserves, transparent monitoring-cost scenarios, and water and soil-biodiversity indicators for stewardship payments.

Keywords: soil organic carbon, carbon farming, greenhouse gas accounting, soil respiration, carbon permanence, nitrous oxide, methane, monitoring reporting and verification, farmer-centred governance, Indonesia

Volume 9 Issue 1 - 2026

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Received: September 15, 2026 | **Published:** November 27, 2026

JEL Classification: Q15; Q54; Q56; Q58; O13.

Introduction

Background: the promise and paradox of agricultural soil carbon

Soil organic carbon (SOC) supports nutrient cycling, aggregate stability, water regulation and biological functioning while constituting an important component of terrestrial carbon storage. Increasing degraded agricultural SOC has consequently become an attractive climate and food-system objective. International syntheses indicate that soil protection and improved management can contribute meaningfully to nature-based mitigation, but they also emphasise that the technical potential is conditioned by land type, management history, baseline stocks, climate, and measurement assumptions. The restoration of a depleted soil may provide real agronomic benefits even when its contribution to the global carbon budget is too uncertain to justify an offset certificate.[1–4]

A frequently overlooked problem is that carbon is simultaneously a stock in soil, a flow between organisms and the atmosphere, and a claim within an economic accounting system. The stock can rise while respiration continues, and a management intervention can affect carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in different directions. A buyer, however, may receive a certificate expressed as one tonne of carbon dioxide equivalent without seeing the uncertainty, monitoring duration, leakage risk, or specific counterfactual embedded in that number. Confusing these dimensions transforms a valuable land-stewardship objective into an accounting shortcut. Literature on soil certification and whole-ecosystem accounting argues for keeping stocks, fluxes, and claims analytically distinct.[5,6]

The central conceptual challenge is not whether soils matter: they do. It is whether temporary and reversible biogenic carbon storage can be treated as an exact substitute for continuing fossil carbon emissions. Fossil-derived atmospheric CO_2 has long-lived warming consequences, whereas biologically accumulated soil carbon may be lost following tillage, drought, land conversion, flooding, erosion or discontinuation of management. Research on durability and climate response shows that short storage can confer a genuine climate benefit while remaining insufficient to neutralize the long-lived effects of fossil emissions. Accordingly, a defensible policy must value temporary storage accurately rather than deny its worth or overstate its equivalence.[7–9]

Urgency in tropical agriculture and Indonesia

Indonesia illustrates why this distinction matters. Its agricultural landscape includes peat systems with large pre-existing carbon reservoirs, irrigated rice with consequential CH_4 dynamics, humid tropical uplands, tree-based production, and highly heterogeneous small farms. The climate-optimal action is therefore not uniform: protecting a peat carbon stock may avoid large future losses; changing paddy-water management may curb ongoing methane; and tree-based agriculture may improve both aboveground inputs and soil condition.

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An extensive synthesis of Southeast Asian croplands nevertheless documents important evidence gaps and warns that practices which increase SOC can also change non-CO_2 emissions.[10,11]

The governance context is also evolving. Indonesia established a carbon exchange and, on 10 October 2025, enacted Presidential Regulation No. 110 of 2025 governing carbon economic-value instruments and national greenhouse-gas emission control, replacing Presidential Regulation No. 98 of 2021 (official text: https://peraturan.go.id/id/perpres-no-110-tahun-2025). These policy developments create scope for transparent performance finance, but existence of a trading architecture alone does not prove the environmental integrity of individual agricultural units. Likewise, the European Union's Carbon Removals and Carbon Farming Certification Framework establishes an institutional reference for differentiating activities and assigning monitoring and liability requirements. In both settings, the credibility of claims ultimately rests on physical evidence and accountable institutions, rather than certification terminology.

Research gap, purpose and contribution

Existing publications often concentrate on one segment of the problem: SOC sequestration potential, methods of detecting stock changes, a particular gas, project profitability, or carbon-credit integrity. Although each is useful, their separation can obscure interactions. Sampling methods adequate for national inventories may not support high-certainty field-level payments; aggregate SOC trends can coexist with episodic N_2O peaks; and stringent additionality rules may exclude early adopters whose stewardship is socially desirable. A synthesis across biophysical, measurement, temporal and distributive perspectives is therefore needed.[12–14] A protocol-level comparison also found substantial divergence in the scientific rigour of methods used to quantify initial stocks and subsequent changes; this supports assessing the quality of each crediting methodology rather than treating certification as sufficient evidence.[15]

This article develops a qualitative, explanatory synthesis organized around four research questions: whether a claimed soil-carbon change is real, whether the resulting carbon remains stored, whether total climate effects are positive when all gases and boundaries are considered, and whether incentive systems treat participating farmers fairly. Its specific contribution is to connect the four questions to a practical decision logic for tropical agriculture, emphasizing protected carbon stocks, rigorous measurement, conservative climate claims, and incentives for continued stewardship. It also proposes a locally adaptive architecture linking farms, scientific observation sites, extension services, cooperatives, verifiers, and public regulators.[16,6]

Literature review: conceptual and theoretical foundations

Carbon stocks, ecological flows and the difference between storage and sequestration

A soil carbon stock refers to carbon held within a specified mass or volume of soil at a given time. Sequestration is the increase in that stock attributable to atmospheric carbon uptake, subsequent plant transfer, and retention, relative to a meaningful baseline. A stock difference is not necessarily a sequestration flux: it may reflect soil-mass changes, redistribution, imported organic inputs, erosion or measurement noise. Depth, bulk density, gravel fraction and equivalent-soil-mass corrections affect stock estimates. Interpreting SOC concentrations without these components risks treating a measurement artefact as mitigation.[17] Direct comparisons of fixed-depth and equivalent-soil-mass accounting further show that soil compaction and changes in bulk density can materially alter inferred sequestration amounts, even where measured concentrations appear comparable.[18,19]

The carbon-balance relationship is conceptually straightforward but ecologically dynamic: change in SOC equals organic carbon inputs minus respiratory, dissolved, erosional and other outputs, integrated over a defined period. Roots, litter, residues, manure and compost increase inputs; microbial decomposition and physical redistribution determine how much remains. Temperature, water, mineral protection, aggregation and plant composition alter stabilization and turnover. The proportion retained in mineral-associated organic matter and particulate organic matter can respond differently to environmental change, challenging any fixed claim that a particular practice always generates the same durable carbon increment.[20,21]

Soil respiration and microbial processes

Soil respiration measures carbon dioxide emitted from the soil surface through a mixture of root-associated activity and heterotrophic decomposition, depending on the measurement method and ecosystem. An increase in respiration is not, by itself, proof of a deterioration of the overall soil carbon balance: productive systems may have both larger inputs and larger outputs. Conversely, an apparently low CO_2 efflux can coincide with low biological activity or lack of plant carbon supply. Mechanistic attribution requires concurrent information on vegetation, hydrology, temperature and stocks. This is especially pertinent in agroforestry, where enhanced microbial activity may accompany improved carbon storage.[22,23]

The distinction between total and heterotrophic respiration is crucial in drained peat. Emissions associated with oxidation of previously stored peat carbon represent degradation of an old carbon reservoir, while root respiration is part of a faster contemporary plant–soil cycle. Rewetting studies from Riau and West Kalimantan demonstrate how hydrological interventions can reduce peat CO_2 losses even when CH_4 responses are more complicated or site-specific. Thus, hydrological context must accompany any generic assertion about the relationship between soil organic matter and carbon emissions.[11,24]

Biogeochemical trade-offs between CO_2, CH_4 and N_2O

Net climate accounting cannot stop at SOC because anaerobic conditions and nitrogen transformations may generate other important greenhouse gases. Flooded rice promotes methanogenesis, whereas periods of soil aeration can suppress CH_4 production but alter nitrification and denitrification, potentially increasing N_2O. Methane and nitrous oxide differ in atmospheric lifetimes and radiative effects; their exchange cannot be inferred from SOC stocks. This is a fundamental reason to measure management outcomes as net, gas-specific effects and to state the selected global warming potential metric explicitly.[25–27]

N_2O is particularly challenging because important portions of annual emissions may occur during short, event-driven windows after rainfall, fertilization, thawing or rewetting. Sparse chamber observations and generic emission factors risk missing the magnitude of these peaks. High-frequency instruments, event-sensitive field protocols and data analysis can expose temporal heterogeneity that otherwise disappears into annual averages. Regional and global modeling remains useful for screening and national estimation, but localized verification requires careful calibration against observed fluxes.[28,29]

Citation: Judijanto L. Beyond soil carbon credits: integrating greenhouse gas accounting, soil respiration, carbon permanence, and farmer-centred climate governance. *Open Access J Sci.* 2026;9(1):528–538. DOI: 10.15406/oajs.2026.09.00337

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Carbon permanence, saturation and reversal risk

SOC accumulation does not necessarily continue indefinitely. As inputs and losses move toward a new equilibrium, marginal sequestration rates commonly decline, and warming or altered land use can reverse previous gains. Long-term experiments, syntheses and carbon-model studies all caution that management effects depend on soil texture, starting carbon concentration, external input availability and time since adoption. Moreover, an increase in one horizon may be offset by a decrease elsewhere in the profile, requiring depth-consistent measurement.[30–32]

The distinction between reversible biological reservoirs and more durable carbon dioxide removal creates a problem of temporal matching. A decade-long contract is not equivalent to a guarantee that carbon remains isolated from the atmosphere for centuries. Climate scientists increasingly distinguish the physical temperature effects of temporary storage from permanent neutralization. The implication is not that short-lived land interventions are worthless; they may delay warming, reduce near-term pressure and improve resilience. Rather, claims should specify storage duration, future replacement or reversal responsibilities, and which emissions are allegedly compensated.

Additionality, leakage, measurement uncertainty and institutional credibility

Environmental integrity in crediting requires at least a robust baseline, additional change caused by an intervention, conservative quantification, surveillance of displacement or leakage, prevention of double counting, and responsibility if stored carbon is released. Counterfactuals are inherently uncertain because farms face evolving prices, regulations, rainfall, soil conditions and farmer preferences. A plausible baseline therefore needs more than an unchecked historical average. Critical assessments show that market methodologies can materially over-credit project benefits, although evidence from other project categories should not be mechanically generalized to all soil projects.[33,34] The methodological variation documented across soil-carbon protocols reinforces the need to disclose stock-calculation methods, sampling depth, baseline treatment and conditions for recalibration.

Quantification also has a scale problem. Soil carbon changes may be hard to detect confidently on an individual field over a short period, but aggregated, well-designed samples across multiple fields can detect meaningful management responses. Digital soil maps and remote sensing can improve spatial stratification and reduce sampling expense; they cannot independently observe an enduring soil-carbon stock gain beneath every pixel. A credible monitoring, reporting and verification (MRV) design combines physical samples, calibrated models, repeat observations and full uncertainty disclosure.[35–37] A recent cross-scale review similarly identifies limited field measurements and incomplete integration between models, direct observations and accounting systems as constraints on credible agricultural greenhouse-gas reporting.[38]

Farmer-centred governance and ecosystem-service valuation

A scheme's viability depends not only on measured environmental outcomes but also on participation costs, tenure security, extension services, liquidity, risk allocation and farmers' non-financial motivations. Payment schemes may fail when sampling costs precede uncertain future revenue, rules are hard to understand, or aggregators capture most benefits. Studies from Australia and India highlight these practical challenges, including selection effects that can exclude smaller or disadvantaged farms. Coordinated groups and existing cooperatives can strengthen knowledge exchange and bargaining, although pooled carbon projects also introduce governance and liability complexity.[39] Evidence from UK agricultural carbon-market studies also shows that farmers require credible, usable information on contract terms, anticipated returns and market governance before commitments can be meaningfully informed.[40,41]

An ecosystem-services perspective broadens the value proposition. Soil protection improves infiltration, reduced erosion, drought buffering, ecological diversity, and productive capacity under context-dependent conditions; these benefits may justify support even when robust carbon offset credits are infeasible. Syntheses of agroforestry and diversified land management support soil-health benefits while showing substantial regional and management-specific heterogeneity. Consequently, a performance contract should permit measurable soil and resilience indicators alongside conservative greenhouse-gas metrics.[42–44]

Method: qualitative literature review

Review design and epistemological orientation

The study adopts a qualitative literature review (QLR), not a systematic literature review or quantitative meta-analysis. Its purpose is theoretical integration and interpretive explanation across distinct knowledge domains: soil biogeochemistry, climatic time horizons, measurement systems, environmental economics and agricultural governance. Unlike protocols designed to deliver exhaustive search reproducibility or pooled effect sizes, the review uses purposive selection of influential and relevant peer-reviewed contributions to compare mechanisms, causal arguments, contradictions and institutional implications. It does not claim to have conducted PRISMA screening, risk-of-bias scoring for every candidate study, or novel numerical synthesis.

Literature identification and selection

The review focuses on peer-reviewed journal articles published between January 2020 and October 2026 and gives priority to journals covering soil science, global change, land use, environmental management, climate policy and rural development. Search themes included soil organic carbon and permanence; soil respiration; CO_2, CH_4 and N_2O fluxes; peat rewetting; alternate wetting and drying; carbon-farming certificates; carbon markets; MRV; remote sensing; sampling uncertainty; cooperatives; and equity.

Selection emphasised publications that could explain a particular mechanism or reveal a material tension. For example, papers on carbon-pool potential were juxtaposed with work on durability and reversals, and papers on soil sampling were compared with emerging digital MRV approaches. Direct Indonesia and Southeast Asia studies were deliberately included so that international findings would not be uncritically transplanted into tropical peat, rice and smallholder contexts. Where the evidence was heterogeneous, the review records conditional patterns rather than manufacturing pooled or nationally representative estimates.

Interpretive synthesis and limitations

After familiarisation, sources were grouped into four deductive themes: reality of measurement, persistence, net greenhouse-gas effects and fairness. Inductive cross-cutting themes were then identified, including the distinction between stock and flow, the incompatibility of short monitoring horizons with long offset claims, the importance of hydrological management, the scale-dependence

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of MRV accuracy and alternatives to offset-funded incentives. The synthesis followed an argument-by-argument comparison of convergence, tension, transferability and policy implications, without claiming to be a systematic coding exercise.

Three limitations apply. First, selected research cannot guarantee coverage of every relevant empirical study, because purposive synthesis is not an exhaustive census. Second, the findings are not new field measurements, nor does the review report an independent greenhouse-gas inventory or causal program evaluation. Third, institutional rules and carbon-market methodologies evolve; policy references are contextual background rather than peer-reviewed journal references, and legal applicability should be reconfirmed before regulatory deployment. These boundaries strengthen, rather than weaken, the distinction between a conceptual model and verified project-level credit issuance. The supplementary numerical examples in Sections 4.2 and 5.1 are illustrative policy and budgeting calculations informed by published standards and measurement-cost evidence; they are neither pooled estimates nor observed Indonesian project costs.

Results: thematic findings

Theme I — Is the carbon gain real?

The first finding is that uncertainty is inherent to soil-carbon measurement but can be managed through experimental design. SOC stock estimates depend on laboratory determination of concentration, representative depth, bulk density, coarse fragments and spatial variability. Repeated samples must be comparable through time and adjusted for differences in soil mass. The sampling problem is asymmetrical: a large existing stock must be measured sufficiently precisely to detect a comparatively small incremental change. Investigators consequently recommend project-scale aggregation, sampling stratification and explicit uncertainty intervals rather than overconfident field-specific declarations. This concern is not merely theoretical: an analysis of fixed-depth soil sampling showed how changes in bulk density can substantially misstate the direction or magnitude of stock change, supporting equivalent-soil-mass corrections and depth-stratified interpretation.

Remote sensing provides complementary information on land cover, vegetation, crop rotations, soil exposure and environmental covariates; it cannot directly substitute for measurements of subsurface organic carbon under vegetation. Machine-learning maps may identify where sampling is most informative but can inherit biases from uneven source data, local calibration gaps and extrapolation beyond observed soil types. Regional ensemble modeling and broad-scale mapping reviews both favor representative training data and independent validation. More recent MRV architecture explicitly combines physical samples, spatial prediction and uncertainty deductions in the credit calculation. Monitoring approaches should therefore be evaluated against transparent measurement protocols, because internationally used carbon-credit quantification systems can differ materially in scientific stringency.

Measurement frequency must also fit the phenomenon. Continuous or automated chambers may resolve highly variable gas fluxes over hours and seasons, whereas stock changes typically require multiyear comparison. Eddy covariance observes turbulent exchange over a footprint with distinct spatial and analytical boundaries. Neither approach by itself resolves every attribution problem: ecosystem CO_2 exchange must be decomposed into photosynthesis, respiration and land-management effects, while stock changes require robust comparison across profiles. Accordingly, the claim that one instrument can verify an entire agricultural carbon credit is methodologically unsound. For practical reporting, integrated sensor, model and sampling systems must also acknowledge differing spatial and temporal supports; a field-scale estimate is credible only when the associated data gaps and uncertainty are explicit.

The fourth finding under this theme concerns baselines. An observed increase in SOC does not prove that a buyer-funded intervention caused it; local rainfall, land-use history, management trends, external material transfers and independent farmer incentives may also explain change. For certification, additionality is therefore an empirical and contractual question, not an intrinsic property of cover crops or agroforestry. Project evaluation research warns that weak counterfactuals generate over-crediting; governance frameworks should document both physical change and the plausible intervention-specific increment.[33] Figure 1 presents the four connected integrity gates used to evaluate soil-carbon mitigation claims. It distinguishes credibility of measurement from durability, net greenhouse-gas impact and contractual fairness, so that success in one dimension cannot compensate for failure in another.

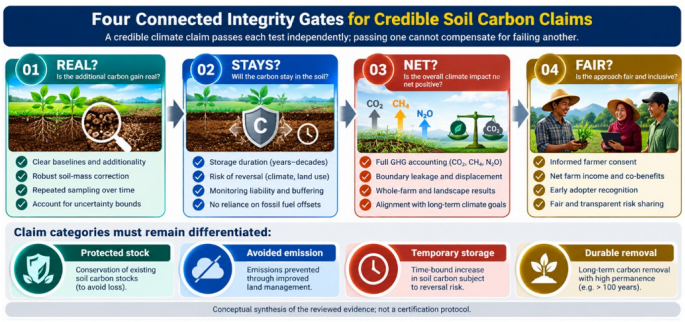

Figure 1 Four integrity gates for credible soil-carbon claims. Conceptual synthesis based on the reviewed literature.

A project cannot pass the integrity test through a single stock-increase estimate: the claim must also withstand durability assessment, a whole-gas check and distributive governance scrutiny. Although the gates are sequenced for auditability, their requirements interact through the baseline, monitoring period, contractual duration and farmer obligations. Failing a gate need not invalidate the underlying agronomic intervention; instead, it can require a narrower claim or a different finance instrument.

Theme II — Will the carbon remain stored?

The second major finding is that a larger SOC stock should not be mistaken for a secure, isolated vault. Organic inputs and decomposition respond continuously to land management and climate. Controlled changes such as residue retention, cover crops and manure may increase SOC, but rates and persistence vary with soil and management conditions. A synthesis of management practices found positive but uneven carbon responses, while another global synthesis confirmed that site effects and starting conditions are essential to estimating realized potential.[30,32]

Carbon protection differs from carbon accumulation. Preventing drainage or conversion of high-carbon peatlands avoids the destruction of pre-existing stocks that may not be recoverable on policy-relevant horizons. Global research identifies peat and other carbon-dense ecosystems as priorities because potential losses are large and replacement is slow. The preferred mitigation sequence therefore often protects existing stocks before seeking smaller additional increments elsewhere. This strategic hierarchy is particularly compelling for Indonesia, where drained peat may continuously lose carbon and generate fire risk.[45,46]

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Comparative agronomic studies show that management durability is practical as well as biochemical. Residues, no-tillage, deep cultivation, woody integration and amendments interact differently with soil profile and rainfall. Reduced disturbance may improve surface carbon but require deeper sampling to rule out redistribution, while agroforestry may produce sustained woody inputs but take time to establish. Global meta-analyses and field syntheses therefore support portfolios selected by ecosystem context rather than universal crediting factors for individual practices.[47–49]

A climate claim must finally specify time. Research distinguishing temporary storage from equivalent permanent neutralization demonstrates that delaying CO_2 release is not the same as eliminating its eventual warming effect. Long-term liability requires reserves, buffers, replacement obligations or public governance arrangements proportionate to the risk of future reversal. It would be inappropriate to infer that every soil-carbon intervention lacks climate value, but equally inappropriate to market a decade of unverifiable custody as a permanent offset for a continuing fossil emission.

Risk-based buffer withholding provides a practical institutional response to non-permanence. For example, Verra's AFOLU Non-Permanence Risk Tool v4.2 establishes a 12% minimum contribution for projects subject to the tool, with higher contributions determined by internal, external and natural risks, including projected climate impacts. ACR's 2024 risk tool instead determines project-specific contributions for unintentional reversals using geographically explicit natural-disturbance information. These are version-specific examples, not a universal 10–20% rule; the applicable protocol, transition provisions and risk assessment must be confirmed at each verification.[50–52]

For illustration, assume 1,000 tonnes CO_2-equivalent of eligible, conservatively quantified stock-based benefit before buffer withholding and no other issuance deductions. A 12% reserve deposits 120 tonnes and leaves 880 tonnes potentially issuable; 15% and 20% reserves deposit 150 and 200 tonnes and leave 850 and 800 tonnes, respectively. In this simplified example, the potentially issuable quantity equals the eligible quantity multiplied by $(1 - b)$, where b is the buffer fraction. The 15% and 20% values are sensitivity scenarios rather than prescribed rates; the actual contribution may exceed 20%, and a project with unacceptable risk may be ineligible altogether. This reserve is distinct from an uncertainty deduction and does not apply automatically to already-achieved CH_4 or N_2O reductions under the cited Verra tool.[50]

Theme III — Is the intervention net-positive across gases?

The third finding is that greenhouse-gas trade-offs are system dependent and sometimes decisive. In rice production, alternate wetting and drying (AWD) can reduce methane through intermittent aeration, but the same aeration episodes may stimulate nitrous oxide or affect crop water stress. A 2024 global meta-analysis estimated average CH_4 reduction of 51.6%, increased N_2O of 44.0%, and a 46.9% decline in the combined global warming potential of CH_4 and N_2O relative to continuous flooding across its sample; those numbers describe pooled comparisons, not a guaranteed Indonesian farm response. Consequently, the management threshold, fertilizer regime, soil properties and local monitoring remain critical.

Peatland rewetting reverses the logic of drainage-driven carbon oxidation but requires careful attention to the full gas profile. Indonesian studies report reduced soil CO_2 losses after rewetting, alongside context-dependent methane behavior and often lower nitrous oxide. In Riau, rewetting reduced heterotrophic respiration and was associated with higher CH_4 at some locations, while a West Kalimantan study found marked reductions in peat CO_2 after rewetting without a clear CH_4 increase relative to drainage in its sampled sites. These results cannot be reduced to the sweeping statement that rewetting is always carbon neutral or always increases methane; baseline condition and vegetation matter.

Figure 2 clarifies the accounting distinction between a carbon stock, the carbon fluxes that change that stock, and the independent assessment of greenhouse gases. It emphasizes that nitrogen-derived N_2O emissions are not a carbon output and that gross soil CO_2 respiration should not be counted again when its carbon loss is already represented in a measured stock change.

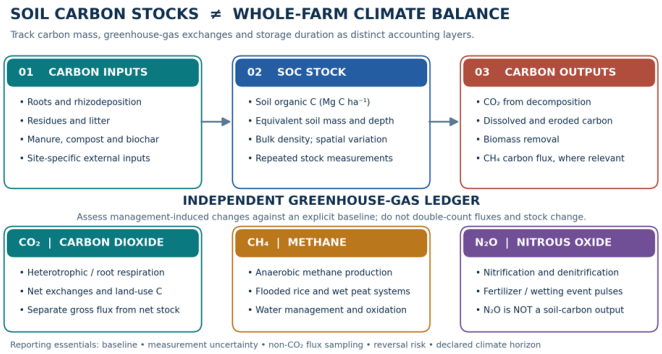

Figure 2 Carbon inputs, SOC stocks and carbon outputs linked to an independent CO_2-CH_4-N_2O ledger. Conceptual accounting diagram developed for this review.

Plant inputs, carbon losses and physical soil measurements together explain observed changes in SOC stocks; they do not independently establish the climate consequence of a management practice. The lower layer therefore evaluates CO_2, CH_4 and N_2O against an explicit baseline and with matching spatial boundaries and observation periods. A credible verification report should disclose stock change, gas-specific fluxes, uncertainty and storage duration separately.

Nitrogen management demands particular attention because episodic N_2O peaks can dominate poorly sampled annual inventories. Temperature, precipitation, soil acidity, moisture, available nitrogen and management event timing determine how nitrification and denitrification proceed. High-frequency flux campaigns, sampling triggered by wetting and fertilization, and calibrated emission-factor databases are therefore essential complements to low-frequency national estimation. Research on post-fire trace nitrogen fluxes further shows that disturbances alter nitrogen pathways in ways that generic annual baselines may fail to capture.

The net effect also depends on system boundaries. Transporting manure or biochar can move carbon from one field to another without increasing the amount removed from the atmosphere at the wider system scale. Fertilizer production, irrigation pumping, residue displacement, livestock feed substitution and yield-related land expansion can create indirect emissions or leakage. Comprehensive ecosystem accounting therefore tracks changes in all reservoirs and substantial upstream or downstream effects, while distinguishing net carbon removal from avoided emissions.

Theme IV — Is the arrangement fair and viable for farmers?

The fourth theme shows that transaction-cost structure can determine who enters a carbon market. Small farms generally

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face a disproportionate burden from mapping, repeated sampling, reporting, assurance, legal review and delayed payment. Australia-based research identifies uncertainty about returns, information gaps, project complexity and upfront costs as barriers. Collaboration among landholders can help share information and improve negotiating power, but complicated joint liability arrangements may create additional risks. Public extension, trusted cooperatives and simple contracts can therefore matter as much as carbon prices. Complementary research from the UK highlights the importance of accessible market information and the risk of mismatched expectations between carbon buyers and participating farmers.[40,41]

Additionality can unintentionally punish early adopters. A farmer who maintained cover crops, trees, soil fertility or wet peat before a project begins may generate no newly creditable increment even though those practices protect a valuable environmental service. In contrast, a recently degraded field may display a higher apparent opportunity for rapid additional sequestration. Such asymmetry may reward the wrong historical sequence if interpreted without safeguards. Equity-aware payment design should distinguish transitional incentives for new action from stewardship payments for continued maintenance of existing ecosystem condition.

Sociopolitical participation must also be measured. A study of Indian carbon-farming projects found concentration among larger holdings and evidence of gender and social exclusion, alongside delays or absence of monetary benefits for many surveyed farmers. These findings are context specific, but they illuminate generic risks for Indonesian programs with heterogeneous tenure and strong farmer–intermediary power asymmetries. Registration, accessible grievance systems, benefit-sharing disclosure and choices between individual and collective participation should therefore be central program design questions.

Finally, farms receive services that are not well expressed as a single carbon price. Long-lived rotations, productive soils and improved infiltration support adaptation and yield security, while agroforestry enhances habitat and often builds carbon inputs. Studies from tropical and temperate systems find positive average responses but large heterogeneity in soil-carbon and biological indicators, cautioning against generic benefit claims. Programs should enable farmers to choose ecologically suitable packages and should assess soil health, income stability, water resources and biodiversity as co-objectives rather than incidental bonuses.

Operational water and soil-biodiversity safeguards

Ecosystem-condition payments should use a small, auditable indicator set that reflects soil functions and the receiving landscape, rather than assuming that more SOC guarantees ecological improvement. The following proposed indicators can be recorded alongside carbon observations and evaluated against local baselines or comparable reference sites. Soil-health research supports integrating physical, hydrological and biological indicators because the relationship between each indicator and ecosystem functioning is context dependent.

Water safeguards can include groundwater-table depth (cm relative to the soil surface) in peat, days of inundation and irrigation water use (m^3/ha per crop season) in rice, and infiltration rate (mm/h) or ground cover (%) in uplands. Peat water levels should be measured with representative wells or loggers at least weekly, or continuously where feasible; rice water levels should be recorded through wetting–drying cycles; upland infiltration should be assessed under standardized seasonal conditions. Where runoff or downstream water impacts are material, collect nitrate-N and phosphate-P (mg/L) and turbidity (NTU) at representative inflow/outflow points during relevant wet- and dry-season or runoff events. Targets must reflect ecosystem-specific hydrology, legal requirements, crop performance and site baselines rather than an arbitrary universal threshold.

Soil-biodiversity safeguards can include macrofauna abundance (individuals/m^2) and broad taxonomic-group richness using replicated, fixed-area soil monoliths or equivalent standardized field methods, with earthworms, ants and termites recorded separately where appropriate. A complementary functional indicator is β-glucosidase or phosphatase activity, expressed as micromoles of assay product per gram of dry soil per hour under a specified laboratory protocol. Enzyme activity indicates biochemical function, not species richness; moisture, temperature, soil type and management history must therefore be recorded to interpret it. Repeat biological observations at comparable seasonal stages at least annually in pilot sentinel plots, with trained cooperative enumerators and periodic laboratory quality checks.

For payment design, cooperatives and scientists should agree on baseline ranges, minimum acceptable conditions, monitoring frequency, responsibilities and uncertainty before enrollment. No-conversion and no-new-drainage rules for protected ecosystems, legally compliant water quality and locally appropriate habitat protection act as non-compensable safeguards: a carbon gain cannot override a serious verified breach. Where indicators show deterioration, the program should investigate causes, provide remediation support and withhold only the affected performance payment when justified by the contract; events outside farmer control should trigger adaptive management rather than automatic punitive sanctions. Continued maintenance of good ecosystem condition, including by early adopters, can qualify for stewardship payments without being misrepresented as additional offset credits.

Cross-cutting finding — scientific uncertainty and claim differentiation

Across themes, credible climate governance requires a hierarchy of claims. An emissions reduction can be counted where a credible counterfactual demonstrates that an intervention has prevented emissions that otherwise would have occurred. A carbon removal requires demonstrable atmospheric uptake and storage, with durability treated separately. A stewardship contribution may deserve payment because it improves resilience, protects existing carbon or lowers ecosystem risk, even when it cannot satisfy rigorous offset-equivalence criteria. These categories should be disclosed distinctly in product labels, government accounts and buyer communications.

Discussion and analysis

Resolving the first research question: credible evidence, not frictionless measurement

The literature suggests that credibility does not require universal continuous measurement on every smallholding, which would be prohibitively costly, but it does require a defensible sampling architecture tied to the intended claim. An initial stratification by soil type, management history and land use can prioritize benchmark fields; repeated physical samples provide stock change estimates; chambers or towers characterize gas dynamics where they are decision relevant; and spatial models extend inference only within validated domains. Aggregated projects can reduce variance and spread fixed costs while retaining audit trails back to participating holdings.

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Such architecture must avoid confusing prediction accuracy with causal identification. A remote-sensing model may explain spatial variation in existing SOC yet remain unable to identify whether a specific paid intervention caused an increase. Counterfactual comparison groups, pre-intervention records, management logs and ex-post calibration are therefore essential. A physical measurement is necessary for many project claims but not sufficient for additionality. This distinction explains why precise-looking maps can coexist with fragile offset baselines and why verification must combine biophysical and socioeconomic data.

The cost comparison should distinguish a measured price per sample from a complete MRV budget per hectare. A German field evaluation reported approximately EUR 44 per laboratory observation (including GPS-referenced composite sampling and laboratory services) versus EUR 3–4 per field-sensor observation (including equipment rental and field labor); the sensor did not meet the study's standalone precision criterion. This supports a hybrid calibration strategy, not a substitution of cheap sensor readings for defensible stock measurements.[53] Cost-model research further shows that monitoring expenses depend on project size, design, monitoring approach and protocol requirements.[54]

An illustrative per-campaign budget for a 1,000-ha cooperative assumes one observation location per hectare and a planning conversion of US$1.10 per EUR (not a spot exchange rate). Conventional laboratory-based concentration measurement at all 1,000 locations would cost approximately US$48.40/ha (1,000 × 44 × 1.10 / 1,000). A hybrid design with sensors at all locations, laboratory reference observations at 250 locations (25%), and an assumed US$8–12/ha allowance for spatial modeling, calibration and independent validation would cost approximately US$23.40–28.50/ha: US$3.30–4.40 for sensing, US$12.10 for laboratory reference measurements, and US$8–12 for the modeling allowance. These are transparent planning scenarios derived from the published unit costs and explicit assumptions, not measured Indonesian tariffs or proof of equivalent accuracy.

The example covers the SOC concentration-monitoring component only, per measurement campaign, not full project MRV or annual expenditure. Both designs need separately budgeted bulk-density and coarse-fragment measurements, repeat depths, additional sampling where required, transport not already included in unit rates, greenhouse-gas monitoring, data management, reporting, independent verification and administrative costs. A pilot must determine sample density and the reference subset using the minimum detectable stock change, spatial variability and required uncertainty; it must retain independent validation and expand laboratory sampling when sensor or model errors are excessive. Cooperative aggregation is economically beneficial only when lower expenditure does not undermine measurement integrity.

Resolving the second research question: the correct value of temporary storage

SOC enhancement should be evaluated as a time-indexed service rather than a binary permanent-or-worthless outcome. Stable inputs, lower erosion and better protected soils can store additional carbon for meaningful periods and support more resilient food systems. Nevertheless, the reversal risk cannot be eradicated by an ordinary short commercial contract. The scientifically defensible approach is to disclose duration, commit to monitoring and liability, and avoid treating a temporally limited removal as freely interchangeable with permanent fossil-emission neutralization.

The 2026 climate-physics literature strengthens this differentiation. Temporary removal can have a meaningful role in addressing short-lived climate forcers under carefully specified assumptions, but no universal tonnes-for-tonnes conversion renders short-lived storage a perpetual offset for fossil CO_2. A financing program can therefore be designed around avoided CO_2 releases, climate contributions, or temporary storage services with explicitly constrained claims. This creates a route to pay for valuable stewardship without making invalid equivalence assertions.[55]

A reversal reserve is a contingent liability mechanism, not a physical guarantee of indefinite storage. For Indonesian projects, the risk assessment should reflect correlated drought, fire, peat drainage, flooding, land-tenure insecurity, and management discontinuation; reserve adequacy should be reassessed at verification and after material changes in risk. Contracts should specify the monitoring period, loss-reporting triggers, who pays for replacement units or remediation, and the treatment of intentional versus unintentional losses. Cooperative or program-level reserves and publicly supported disaster-risk arrangements can protect farmers from disproportionate liability, but cannot turn short-lived storage into permanent fossil-carbon neutralization.

Resolving the third research question: all-gas accounting and mitigation hierarchy

The evidence supports a prioritized portfolio rather than an undifferentiated soil-carbon credit target. Where highly vulnerable carbon stocks exist, preserving them first is often more urgent than attempting to create new incremental carbon elsewhere. For drained peat, hydrological recovery can reduce continuing losses; for rice, carefully implemented AWD can generate methane mitigation, with N_2O and yield safeguards; for upland croplands, residue, cover and organic-input packages may improve soil health and SOC; and for tree-based systems, agroforestry may improve carbon inputs and ecosystem functioning. The priority depends on site-specific baseline emissions, feasibility and permanence.

This portfolio requires appropriate system boundaries. Protecting peat soil carbon is not identical to producing a new removal; paddy methane abatement should not be casually relabeled as SOC sequestration; and planting trees cannot be assumed to deliver only subsurface storage. Separate accounting modules can record avoided emissions, removals, protected existing stocks and ancillary ecosystem services. Such modularity improves national inventories, buyer disclosure and program learning, while reducing incentives to monetize the same climate outcome under multiple labels.[56]

Resolving the fourth research question: equitable contracts and stewardship finance

Fairness requires attention to the distribution of risk and timing of rewards. Farmers may pay immediate costs for inputs, water infrastructure, access permissions, monitoring and changed practices, while receiving credit revenue only after verification years later. A poorly designed program transfers measurement error, market volatility and reversal liability to the weakest participant. Agreements should disclose fees and payment triggers, provide accessible dispute resolution, respect legitimate tenure arrangements and avoid disproportionate sanctions for events beyond farmers' control. Communication should make the distinction between stewardship rewards and tradable offsets explicit, since farmer perceptions and program participation respond to the clarity and trustworthiness of information supplied.

Citation: Judijanto L. Beyond soil carbon credits: integrating greenhouse gas accounting, soil respiration, carbon permanence, and farmer-centred climate governance. *Open Access J Sci.* 2026;9(1):528–538. DOI: 10.15406/oajs.2026.09.00337

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A balanced financing design would combine three instruments: up-front transition assistance, ongoing practice or ecosystem-condition payments, and optional outcome-based rewards where credible estimates exist. Baseline stewardship agreements could explicitly include early adopters so that long-standing soil protectors are not penalised. Additionality would remain necessary for narrowly defined climate credits, while broader conservation finance could support maintenance and adaptation without pretending that every payment purchases a certified atmospheric removal. Such differentiation also offers a policy rationale for cooperative aggregation and public investment in MRV. These design choices are especially important when potential participants face complex and heterogeneous crediting methods; the protocol-comparison literature cautions against presuming uniform rigour across products. The ecosystem-condition component should use the water and biodiversity safeguards in Section 4.4.1, with separately disclosed eligibility thresholds, payment triggers and farmer-accessible grievance procedures. Maintenance payments should remain distinct from any tradable carbon unit.

Indonesia-focused translation: science-to-policy architecture

Indonesia needs differentiated approaches across peat, rice, uplands and agroforestry. A peatland program would make water-table dynamics, land-cover transitions, fire prevention and subsidence central indicators, while separating the protection of existing carbon from any newly accumulated SOC. A rice program would prioritise irrigation practices, methane observation and N_2O safeguards, supported by locally calibrated thresholds. An upland program would emphasise erosion reduction, residue systems, nutrient efficiency, adaptation and soil condition. Agroforestry programs should account for aboveground biomass, root inputs, soil carbon and land tenure separately.[57,58]

The policy task is to convert these differentiated interventions into consistent but non-identical verification protocols. Government can establish publicly accessible benchmarks, quality assurance and long time horizons; universities and institutes can deliver flux measurements, soil laboratories and statistical models; cooperatives can coordinate samples and farmer learning; independent verifiers can evaluate the strength of evidence and permissible climate claims. The division of responsibilities should be transparent, with explicit procedures for data ownership, community consent, audit access, disputes and program exit. International carbon-credit research underlines the risks of opaque methodologies and weak accountability.

Figure 3 translates the four-gate framework into differentiated priorities for Indonesian production systems. It links ecosystem-specific actions and observable indicators to financing instruments rather than applying a single soil-carbon-offset template to peatlands, irrigated rice, upland cropland and agroforestry. Peatland protection prioritizes water tables and long-term stewardship; irrigated rice requires methane and nitrous oxide evaluation; upland cropland emphasizes SOC, erosion and resilience; and agroforestry combines aboveground biomass, soil stocks and landscape safeguards. A shared institutional system could connect cooperatives, field monitoring, laboratories, independent verifiers and public regulators without assuming that these facilities already operate as a unified national program. Protected stocks, avoided emissions, temporary storage and ecosystem-service payments should retain separate accounting labels.

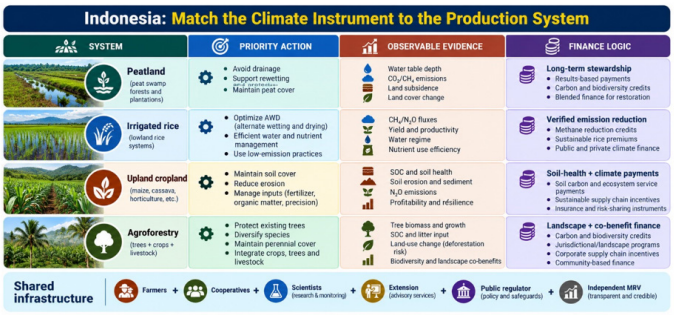

Figure 3 Differentiated climate actions, evidence requirements and financing choices for Indonesian agriculture. Illustrative synthesis developed for this review.

A staged implementation roadmap and accountability indicators

A realistic implementation sequence begins with institutional design and pilot selection rather than mass certificate issuance. During the initial phase, public agencies and local partners should identify representative ecological strata, inventory existing datasets, map tenure and benefits, and establish consent and sampling protocols. Pilot farms should be chosen to cover baseline contrast as well as geographical diversity. The second phase should establish repeated SOC and gas-flux observations alongside management diaries, farmer experience surveys, and laboratory cross-calibration. The third phase can introduce conditional performance payments, independent audits and prospective comparisons of net outcomes against credible baselines. An integrated field-scale measurement perspective also suggests documenting the transferability of models and the density of direct observations before expanding a pilot to new agroecological zones.

Success metrics must go beyond tonnes sold. Credibility indicators include uncertainty intervals around stock changes, completeness of seasonal N_2O and CH_4 observations, consistency of soil-depth definitions, availability of baseline controls, and publicly recorded reversal procedures. Fairness indicators include the proportion of gross program revenue actually reaching farmers, representation of smallholders and women, timely payment, retention rates, informed consent and access to grievance channels. Ecological indicators include soil-cover continuity, hydrological function, erosion reduction, biodiversity and crop-resilience outcomes. No single indicator should obscure trade-offs across the others.[59] For operational consistency, the pilot should report the water and biological indicators defined in Section 4.4.1 alongside their sampling dates, baseline ranges, quality checks and corrective actions.

A useful reporting template would contain four parallel ledgers: SOC stock change (in tonnes C per hectare with uncertainty and depth), gas-specific annual emissions or removals (CO_2, CH_4 and N_2O), storage-duration and reversal commitments, and farmer-level distribution of costs and benefits. Where a climate-equivalent result is presented, the gas-specific quantities and selected warming metric should remain visible. Reporting protected stocks separately from newly credited reductions would avoid conflating a conservation benefit with additional atmospheric removal. This multidimensional account is a direct operational response to the four questions underpinning the review. Importantly, carbon-stock change and cumulative soil CO_2 efflux should not simply be summed as separate net-emission terms where doing so would double-count the same

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carbon losses. Any conversion to CO_2-equivalent should document the selected GWP time horizon, gas-specific quantities and accounting boundaries.

Research implications, unresolved questions and opportunities

Several gaps warrant targeted investigation. One is the transferability of international SOC response factors to warmer, strongly weathered tropical soils, where decomposition, soil minerals, rainfall and management inputs may differ substantially. Another is the long-term interaction between rewetting, vegetation recovery, methane flux, subsidence and peat carbon stability across Indonesian landscape types. Third, the scientific value of hybrid observational designs should be compared with their full monitoring cost when deployed through farmer groups. These questions require multiyear data, transparent protocols and independent replication.

To test the indicative budget in Section 5.1, Indonesian pilots should compare paired laboratory-only and hybrid designs within the same soil strata, depth intervals, observation windows and target precision. Cost logs should separate fixed model development and training from variable sampling, laboratory, gas-flux and audit costs; report both US$/ha per campaign and annualized full MRV cost, alongside uncertainty and the cost per independently verified tonne CO_2-equivalent where appropriate. These comparisons should test scale economies, affordability for smallholders, and whether savings persist when calibration and validation are repeated in new agroecological zones.

A further research priority is social and institutional, not merely technological. Studies should test which contract forms retain farmers without eroding intrinsic stewardship, how early adopters can be rewarded without overstating additionality, and how sampling costs can be shared fairly. Cooperative models offer a plausible avenue but need evaluation for elite capture, bargaining power and data governance. Similarly, the use of climate finance for soil health and adaptation should be evaluated on its own terms instead of being judged only by the number of saleable offset units.

The resulting research agenda calls for a transdisciplinary network rather than isolated short-term projects. Soil scientists can investigate mechanisms and storage, atmospheric scientists can interpret fluxes and climate horizons, economists can assess incentives and transaction costs, and legal researchers can clarify liability and claims. Farmers supply practical experience, historical knowledge and evidence of management continuity that cannot be inferred from satellites alone. Trustworthy reporting emerges when these contributions are integrated, transparently scrutinized and linked to adaptive public policy.[60–65]

Conclusion and recommendations

The central conclusion is that more soil carbon is often desirable, but a measured increase in SOC is not equivalent to a permanent, additional, net greenhouse-gas offset. Climate credibility depends jointly on reliable measurements, adequate storage duration, full CO_2–CH_4–N_2O accounting and fair contractual arrangements. Soil respiration is part of a dynamic carbon balance; carbon permanence is conditional; net mitigation is ecosystem specific; and farmers cannot reasonably be expected to carry indefinite risks under short or opaque contracts.

For Indonesia and other tropical agricultural settings, the recommended mitigation hierarchy is to protect vulnerable peat and other high-carbon ecosystems, reduce demonstrable methane and nitrous oxide emissions, restore degraded soils with suitable practices, and reward ecosystem condition and adaptation benefits. Carbon markets may finance a carefully delimited subset of these outcomes, but payment-for-performance, public stewardship programs, agricultural extension, cooperatives and science-based monitoring are at least as important. Claim differentiation is essential: protected stocks, avoided emissions, temporary storage, and durable removals should never be marketed as automatically interchangeable. Ecosystem-condition payments should be tied to locally calibrated water-table or water-use indicators, soil macrofauna and complementary biological-function measures, supported by clear monitoring responsibilities and safeguards against ecological deterioration.

The proposed four-gate framework offers a practical basis for transparent project design and evaluation. Its implementation requires long-term farmer–scientist partnerships, uncertainty-adjusted monitoring, independent verification, a clear allocation of reversal liabilities, and benefit-sharing rules that include early adopters and smallholders. The deepest lesson is that climate governance should finance the environmental services that soils can genuinely deliver, while refusing to promise atmospheric equivalence that the underlying evidence cannot support. Risk-based reserves should be transparently calculated and periodically reassessed, while hybrid monitoring should be adopted only where cost savings are demonstrated without sacrificing the required precision or shifting unreasonable risk onto farmers.

Acknowledgements

None.

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