International Journal of Global Sustainable Research (IJGSR)
Vol.4 No.10, 2026: 1475-1494

Beneath the Canopy: Rethinking Soil Carbon Sequestration, Greenhouse Gas Balances, and Regenerative Sustainability in Indonesia's Oil Palm Plantations

Loso Judijanto
IPOSS Jakarta
Corresponding Author: Loso Judijanto losojudijantobumn@gmail.com

A R T I C L E I N F O

Keywords : Soil Organic Carbon, Oil Palm, Carbon Sequestration, Regenerative Agriculture, Greenhouse Gas Balance, Peatlands, Land-Use Change, Soil Health, Carbon Verification, Indonesia

Received : 5 August
Revised : 20 September
Accepted: 20 October

©2026 Judijanto : This is an open-access article distributed under the terms of the Creative Commons Atribusi 4.0 Internasional.

A B S T R A C T

Oil palm combines high photosynthetic productivity with disputed greenhouse gas consequences, creating a need to distinguish canopy carbon uptake from durable soil carbon sequestration. This qualitative literature review critically synthesises 57 peer-reviewed journal articles published in 2020–2026. The review integrates evidence on primary production, soil organic carbon stocks and depth distribution, microbial–mineral stabilisation, plantation replanting, residue recycling, peatland hydrology, land-use history, and verification governance. Results indicate that productive mature plantations may exhibit favourable short-term carbon exchange while conversion losses, harvested-carbon exports, and peat oxidation can dominate broader boundaries. Soil carbon responses to plantation age and regenerative management are context-dependent; darker deep-soil horizons are not sufficient proof of an increased carbon stock. Empty fruit bunch recycling, understory cover, and ecological enrichment offer site-specific opportunities, whereas rewetting and conservation require distinct peatland strategies. The study proposes a carbon stewardship–full-boundary accounting–landscape integrity framework and a tiered monitoring, reporting, and verification pathway. Its central recommendation is to protect forests and peat ecosystems, improve existing plantations through measured interventions, and restrict carbon-removal claims to additional, durable, independently assessed outcomes

DOI: https://doi.org/10.59890/ijgsr.v4i10.5
ISSN-E: 3026-4677
https://journalijgsr.my.id/index.php/ijgsr/index

INTRODUCTION

1. The Strategic Significance of Oil Palm and the Problem of Carbon Interpretation

Oil palm is an unusually productive perennial oil crop whose economic significance is particularly pronounced in Indonesia. Oil palm development has affected forest cover, habitats, peat hydrology, and multiple components of the carbon cycle, making the outcome of any sustainability assessment dependent on where plantations are located, what preceded them, and how they are managed (Meijaard et al., 2020; Xu et al., 2022).

An important stimulus for this review is a presentation entitled Soil Carbon and Sustainable Oil Palm Plantation by Budi Mulyanto, as the initial discussion material (Mulyanto, 2026). Yet the presentation does not establish, from those visuals alone, statistically representative equivalent-soil-mass carbon-stock changes or a universally transferable life-cycle greenhouse gas balance. The distinction matters because observation, mechanism, attribution, and verified mitigation occupy different evidential levels (Rahman et al., 2021; Golicz et al., 2025).

2. The Apparent Paradox of High Carbon Uptake and Contested Climate Outcomes

Photosynthesis fixes atmospheric carbon into vegetation, and the rapid growth of productive palms can produce impressive annual carbon fluxes. Gross primary production measures photosynthetic uptake before autotrophic respiration, whereas net primary production subtracts the plant's own respiratory losses. Neither is a measure of long-term soil sequestration or of climate benefit relative to a counterfactual land use. Other investigations show that converting peat swamp forest to plantation creates emissions that cannot be erased by counting palm photosynthesis alone (Cooper et al., 2020; McCalmont et al., 2021). These observations do not imply that carbon-sensitive management of existing plantations is futile. They imply that the question must be reformulated: under which clearly identified environmental, temporal, and accounting conditions does a change in management create an additional, measurable, and durable climate benefit?

3. Research Gaps, Scope, and Contribution

Three interrelated gaps motivate the present synthesis. The first is conceptual: discussion frequently moves without warning between assimilation, biomass accumulation, soil carbon concentration, carbon stock, and net greenhouse gas balance. The second is methodological: comparisons of different plantation ages or contrasting soil colours can conflate treatment effects with initial soil conditions, sampling depth, bulk density, parent material, and past land management. The third is institutional: the language of regenerative agriculture and carbon credits sometimes advances faster than measurement protocols, safeguards for remaining natural ecosystems, and practical arrangements for participating smallholders (Paul et al., 2023; Black et al., 2022; Grabs and Garrett, 2023). The review adds an integrated carbon stewardship–full-boundary accounting–landscape integrity perspective. In that perspective,

improving soils inside existing plantations is valuable, but it cannot be presented as a substitute for avoiding the destruction of forests or high-carbon peat ecosystems (Noon et al., 2022; Quezada et al., 2022).

LITERATURE RIVIEW

1. Carbon Fluxes, Carbon Stocks, and the Hierarchy of Accounting Boundaries

The first conceptual distinction is between a rate of carbon transfer and the amount of carbon already stored. Gross primary production and net primary production describe fluxes over time, typically expressed as carbon per area per year. At least four nested boundaries can be useful: the soil sampling point, the plantation operating year, the complete establishment-to-replanting rotation, and the conversion-adjusted landscape or supply-chain system. An apparent sink under one boundary cannot be promoted to a stronger claim under a wider boundary without gathering the additional evidence that boundary requires (Cooper et al., 2020; Prananto et al., 2020).

Figure 1 distinguishes four nested boundaries that should be specified whenever plantation carbon balance is discussed. The boundaries separate soil-stock measurements from plantation operation, complete rotations, and land-use legacies.

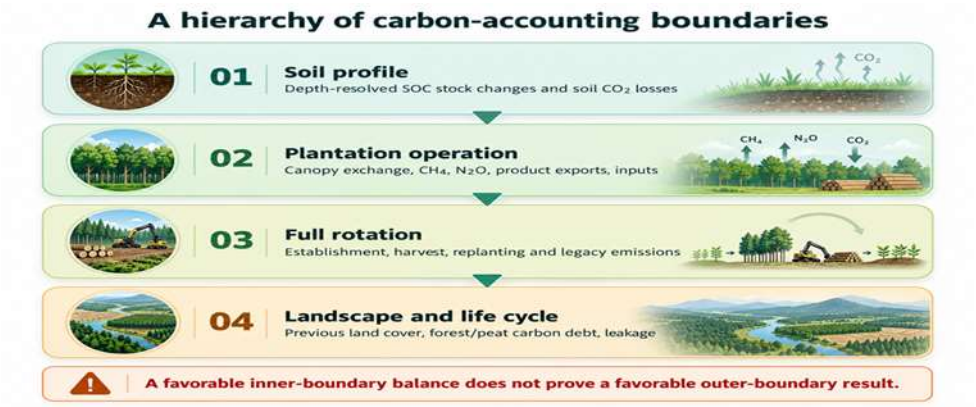


Figure 1. Carbon-Accounting Boundaries Relevant to Oil Palm Sustainability. Conceptual Diagram Developed for this Review; No Empirical Flux Magnitudes Are Implied

Figure 1 illustrates the analytical boundaries that distinguish the soil profile from plantation operations and ultimately from historical land-use change and downstream carbon flows.

2. Soil Carbon Formation, Stabilization, and Depth Distribution

Soil organic carbon is not a single homogeneous reservoir. Root inputs are potentially important because root tissues and exudates enter soil at depth and provide substrates for microbes near mineral surfaces. Yet the effect is conditional: experimental evidence demonstrates that root inputs can stimulate both the stabilization of new carbon and the decomposition of existing organic matter, with outcomes dependent on mineral reactivity (Liang et al., 2023). Thus,

greater belowground input is a credible mechanism for possible SOC improvement, not proof that the resulting stock must rise.

The measurement of depth distribution is especially important for perennial systems. Comparisons should preferably be made at equivalent soil mass to avoid mistaking compaction or loosening for sequestration; regional soil datasets and studies of edaphic controls underscore why spatial heterogeneity and pedological context require deliberate treatment (Wells et al., 2022; Gomez et al., 2024). For a mineral-soil layer i, a fixed-depth SOC stock can be expressed using dry fine-earth carbon fraction (C_i), dry bulk density (BD_i, Mg m^{-3}), layer thickness (Δz_i, m), and the volume fraction occupied by coarse fragments (f_i). The following expression is illustrative rather than an empirical estimate from this literature review:

$$SOC\ stock\ (Mg\ C\ ha^{-1}) = 10^4 \times \Sigma_i\ [C_i \times BD_i \times \Delta z_i \times (1 - f_i)]$$

Here, C_i is a mass fraction (Mg C per Mg fine earth), and 10^4 converts square metres to hectares. An ESM comparison requires interpolation or mass-coordinate alignment to a common reference mass before differences are interpreted as carbon-stock changes (Peng et al., 2024; Dynarski et al., 2026).

3. Plantation Age, Replanting Cycles, and Soil Management Zones

Oil palm plantations are spatially structured rather than uniform fields. Recent observations from commercial plantations suggest that SOC patterns can differ with plantation age, but the relationships are contingent on measured depth, climatic gradients, and management regimes rather than being a universal age law (Golicz et al., 2025).

4. Land-Use Baselines, Carbon Debt, and Ecological Opportunity Costs

The climatic meaning of expanding oil palm is dominated in part by the previous land use. Replacing a carbon-rich forest creates an immediate or cumulative carbon debt, whereas productivity improvements on an existing plantation may improve outputs without creating an equivalent land-conversion penalty. Ecological opportunity cost extends beyond tonnes of carbon. A nuanced analysis can recognize the high yield of oil palm while still concluding that forest protection and avoiding new development on peat are fundamental safeguards.

5. Mineral Soils and Peatlands as Fundamentally Different Carbon Systems

In mineral soils, organic carbon is added through roots, litter, and amendments and can be stabilized by aggregation or association with reactive mineral surfaces. In tropical peatlands, the soil itself consists largely of accumulated organic matter stored under persistently wet, oxygen-limited conditions. The two systems therefore differ not merely in the magnitude of carbon stocks but in the mechanisms governing persistence and potential reversibility (Cooper et al., 2020; McCalmont et al., 2021).

6. Regenerative Management, Ecosystem Services, and Institutions

Regenerative practices relevant to existing plantations include recycling organic residues, maintaining understory cover, limiting unnecessary disturbance, matching fertilizer use to crop demand, and integrating tree islands or protected riparian strips. A synthesis of cover-crop and conservation-agriculture studies in other cropping systems supports the plausibility of some mechanisms, but transfer to humid tropical oil palm must be tested instead of assumed (Jian et al., 2020; Das et al., 2022; Bohoussou et al., 2022). Research on oil palm smallholder production and replanting finds that management improvements and institutional support are consequential for yield and viability (Monzon et al., 2023; Petri et al., 2024).

METHODOLOGY

1. Review Orientation and Identification of Literature

This research applies a qualitative literature review (QLR) using critical, interpretive, and thematic synthesis. It is deliberately not represented as a systematic literature review, meta-analysis, or PRISMA-guided enumeration of the field. The final set contains 57 cited peer-reviewed articles, predominantly concerned with tropical soils and oil palm but augmented by transferable mechanistic and governance literature.

2. Appraisal, Evidence Extraction, and Safeguards

For interpretive purposes, each source is classified by the principal claim it can support: directly measured plantation SOC stocks, micrometeorological or chamber gas fluxes, experimental soil processes, remote-sensing landscape histories, management interventions, or governance and verification principles. The appraisal checks whether authors report soil type, depth and bulk density, plantation age, comparison land use, location and period, and whether the evidence is observational, experimental, model-based, or conceptual.

3. Thematic Coding and Interpretive Synthesis

Iterative reading produced eight interconnected themes: accounting boundaries; plantation age and depth; residue and cover management; microbial-mineral mechanisms; peat hydrology; landscape baselines; measurement and verification; and governance and livelihood conditions. The method distinguishes three interpretive tiers. A directly observed change in a measured stock or flux constitutes a first-tier empirical result under the conditions described by its authors; a process-based explanation for that observation is an inferential interpretation; and a recommendation about policy or certification is a normative implication requiring attention to feasibility and safeguards.

RESULT AND DISCUSSION

1. Theme 1: Assimilation Capacity is Not a Full Greenhouse Gas Account

The reviewed literature makes clear that a productive palm canopy can rapidly assimilate atmospheric carbon without guaranteeing sustained net removal at the ecosystem or landscape scale. The combination is not paradoxical: annual productivity and pre-existing carbon stocks measure different phenomena. The measurements reported by Meijide et al. (2020) distinguish a young plantation operating as a measured carbon source from a mature stand operating as a measured sink over the study interval; these are contrasting empirical observations, not proof that a complete rotation offsets land-conversion emissions.

2. Theme 2: Soil Carbon Age Patterns are Real Research Questions, Not Universal Laws

The supplied photographs from fourth-generation plantation soil profiles show apparently darker material at depth than a neighbouring non-oil-palm profile. Such images can suggest redistribution or incorporation of organic compounds below the surface; they cannot establish whether total carbon stock increased. The strongest defensible inference from the presentation is therefore a hypothesis: repeated replanting and residue management may be associated with persistent deep-soil carbon inputs under some conditions, subject to direct verification.

Figure 2 presents an evidence ladder for testing observations from repeated plantation generations. It emphasises the additional tests needed before a descriptive soil profile can support an attributable sequestration claim.



Figure 2. Evidence Ladder for Interpreting Deep-Soil Carbon Observations and Claims. Conceptual Diagram Developed for this Review

Figure 2 contrasts visible subsoil characteristics, measured SOC concentration, equivalent-soil-mass stock changes and verified sequestration claims.

3. Theme 3: Residue Recycling and Living Cover Offer Opportunities With Constraints

Among plantation management interventions, empty fruit bunches and other organic residues provide a plausible means of returning harvested biomass carbon and nutrients to selected soil zones. Field evidence from an industrial plantation indicates that empty fruit bunch application can affect soil organic carbon, offering support for targeted residue recycling as a candidate management strategy (Noirot et al., 2022). Yet residue addition is not equal to permanent storage: decomposition produces carbon dioxide, some nutrients may be mobilized, and observed changes depend on application rate, placement, duration, and the extent of integration with mineral soil. Evidence from other regions and crops on cover cropping and conservation agriculture supports the general mechanisms of reduced erosion and enhanced organic inputs, but the scale and persistence of responses vary (Jian et al., 2020; Tadiello et al., 2023).

4. Theme 4: Microbial–Mineral Controls Govern the Fate of Added Carbon

A recurring mechanistic theme is that the quantity of plant residue supplied is not sufficient to predict carbon persistence. Root exudates can feed microorganisms, whose transformed products become associated with mineral surfaces, but those same inputs can stimulate respiration and loss of pre-existing carbon. Controlled experiments show that the direction of this balance changes with mineral reactivity (Liang et al., 2023), while global assessments identify substantial differences in mineral-associated carbon capacity (Georgiou et al., 2022). Reviews and experiments on microbial necromass demonstrate that microbial community processes and the route by which microbes die influence the composition of persistent residues (Camenzind et al., 2023; Tian et al., 2024). Initial carbon status can further modify how fertilizer inputs are partitioned between relatively fast-cycling particulate organic carbon and mineral-associated pools. The synthesis by Ling et al. (2025) identifies such dependence in global croplands, reinforcing the need to examine nutrient treatments together with the existing SOC baseline.

5. Theme 5: Peatland Greenhouse Gas Dynamics Override Simplistic Plantation Sink Narratives

On drained tropical peat, the oxidation of previously accumulated peat is a central climate concern. Drainage and soil conditions can alter carbon dioxide and nitrous oxide emissions, while the balance among gases is sensitive to water table, temperature, vegetation and management choices (Prananto et al., 2020; McCalmont et al., 2023). A site that temporarily fixes carbon in growing palms can continue losing ancient soil carbon at the same time. Complementary measurements of drainage ditches in Sarawak show that managed waterways can contribute methane emissions not represented by measurements on the plantation soil alone (Kasak et al., 2025). Rewetting is consequently a different class of intervention from residue addition. Regional conservation and restoration analyses likewise suggest substantial mitigation opportunities from protecting peat swamp forests and mangroves across Southeast Asia (Sasmito et al., 2025). Management recommendations must therefore distinguish peat

conservation, restoration and hydrological repair from ordinary mineral-soil practices, while acknowledging that sustainable long-term use may require transitions beyond conventional drainage-dependent plantation operations.

6. Theme 6: Carbon Integrity Depends on Forest Protection and Ecological Restoration

Landscape studies show that oil palm's environmental effects are strongly conditioned by historical conversion and remaining habitat configuration. Regional maps of plantation establishment, together with evidence that expansion has reached carbon-rich forests, make site-specific land-use chronology essential to any climate claim (Danylo et al., 2021; Xu et al., 2022). The proper priority order is to avoid degradation of high-integrity ecosystems, rehabilitate damaged areas where feasible, and then improve the ecological performance of plantations that remain in production (Noon et al., 2022). Research on set-asides argues that spatial allocation can enhance ecological value, although opportunity costs and local land constraints require attention (Bicknell et al., 2023).

7. Theme 7: Robust Monitoring Requires Repeated Sampling and Multiple Information Streams

Soil carbon measurement is technically more demanding than measuring the carbon percentage in a single sample. Differences in mineralogy, historical land management, precipitation and sampling location can substantially change measured stocks even within apparently homogeneous estate maps (Wells et al., 2022; Gomez et al., 2024). Long-term field research in other agricultural systems shows why trends can be missed or misread when short observation windows and between-site comparisons replace repeated measurements on the same land (Dietz et al., 2024). A single short-term estimate of SOC stock is therefore insufficient as a stand-alone removal claim. Figure 3 summarises the proposed monitoring, reporting and verification sequence. The workflow combines historical land-use integrity with soil sampling, gas-flux observations, and independent assurance.



Figure 3. Proposed Integrated Measurement, Reporting, and Verification (MRV) Architecture for Plantation Soil Carbon. Conceptual Diagram Developed for This Review

Figure 3 translates the evidence into a proposed monitoring architecture, moving from land-use stratification and field sampling through laboratory analysis and gas-flux measurement to uncertainty assessment and independent assurance.

8. Theme 8: Smallholder Incentives and Institutional Credibility Determine Persistence

Smallholders face distinctive challenges in translating regenerative principles into repeatable practices. Yield gaps are influenced by agronomic management, meaning that gains from better nutrient timing, harvest practices and canopy management may be economically attractive even without immediate carbon revenue (Monzon et al., 2023). Multidimensional sustainability assessments further caution that neither farm income nor carbon alone provides a sufficient measure of success (Supriatna et al., 2024). These insights favor policy instruments that reward verified management and environmental improvements without depending entirely on uncertain claims of tradable, permanent atmospheric removals.

Table 1 links each principal theme to its strongest evidence class and the interpretation justified by the current literature. It avoids converting transferability of a mechanism into a universal plantation effect.

Table 1. Overview of Thematic Findings and Legitimate Implications

Theme	Evidence strength	Defensible implication
Assimilation vs balance	Direct oil palm GHG studies	Specify stock, flux, period and boundary
Age / deep SOC	Site surveys and cohort studies	No sequestration claim from colour alone
Residue and cover	Intervention studies plus transferable syntheses	Trial locally and measure SOC stocks
Microbial–mineral mechanisms	Mechanistic experiments	Persistence depends on mineral ecology
Peat dynamics	Field and hydrology studies	Separate peat conservation and rewetting
Landscape safeguards	Historical maps and ecological trials	Avoid forest and peat carbon conversion
MRV credibility	Measurement and carbon-standard analyses	Report soil mass, baseline and uncertainty
Social institutions	Smallholder and governance studies	Design affordable and equitable incentives

Table 1 summarizes the eight themes as a compact evidence-to-decision matrix.

DISCUSSION

1. Resolving the Carbon-Sink Paradox Through Explicit Accounting

The first research question can be answered by recognizing that the expression *carbon sink* describes a balance under specified conditions rather than an intrinsic property of a particular crop. A productive palm may exhibit positive net biomass accumulation while cultivated soil loses carbon, and a mature estate may show negative net exchange over an observation year while the surrounding landscape remains in carbon debt from earlier conversion. As illustrated in Figure 1, no inference should cross from the canopy-flux boundary to the land-conversion-adjusted life-cycle boundary without accounting for the newly included components (Meijide et al., 2020; Murphy, 2024; Cooper et al., 2020). A practical decision framework begins with a counterfactual question: compared with what? If the alternative to improved management is continued cultivation of the same existing mineral-soil plantation, verified SOC gains could be an additional benefit. If the alternative is an intact forest or undrained peatland, the comparison must include foregone standing stocks, soil loss, biodiversity decline and the subsequent fate of harvested biomass. A portfolio of climate indicators is therefore preferable to a single assertion of positive or negative sequestration. The portfolio should disclose biomass stocks, SOC stock change, direct greenhouse gas fluxes, and historical land-use effects separately (Quezada et al., 2022; Noon et al., 2022).

These distinctions have consequences for communications and carbon-market design. A paper that reports a high annual NPP value but labels it soil carbon sequestration is making a category error; a corporate presentation that places annual sequestration beside one-time conversion emissions without a common time base risks a second error.

2. Interpreting Deep-Soil Carbon and Plantation Generations Without Overclaiming

The observation of dark subsoil in a fourth-generation oil palm plantation is scientifically interesting precisely because it is not a completed carbon-stock calculation. A soil horizon may become darker because of organic inputs from roots, dissolved organic matter transported down the profile, preferential water flow, mineral–humus interactions, or differences in the underlying soil. A more intensive sampling campaign would identify matched soil types, replicate sampling by management zone, quantify SOC and bulk density in each depth interval, and use equivalent soil mass as the basis for cross-site or cross-period comparison. Root biomass, soil mineralogy, topography and past disturbance should be documented to reduce hidden confounding (Golicz et al., 2025; Liang et al., 2023). Research on mineral capacity, microbial necromass and SOC fractions supports this more dynamic interpretation (Georgiou et al., 2022; Shabtai et al., 2023; Zhou et al., 2024). High-confidence sequestration attribution requires multi-period measurement, reliable counterfactual plots, and soil-mass-corrected stocks rather than extrapolation from apparent profile darkness. Table 2 specifies the evidence demanded by progressively stronger kinds of soil carbon claims. The framework deliberately separates observational reporting from marketable removal.

Table 2. Hierarchy of Evidence Required for Progressively Stronger Soil Carbon Claims

Claim level	Minimum evidence	Unresolved qualification
Visual observation	Location, dated photographs, matched profiles	Does not quantify SOC
SOC concentration	Validated laboratory test and sample depths	Bulk density may change
SOC stock comparison	Bulk density, fragments, equivalent soil mass	Cross site confounding remains
Stock change attribution	Repeat measurements and credible controls	Additionality and displacement
Credit-grade removal	Full GHG accounting, independent audit, monitoring	Permanence and reversal liability

Table 2 sets out a hierarchy of claim strength and the data needed to make each claim defensible.

3. Choosing Regenerative Practices by Soil Condition and Measured Trade-Off

The fifth research question asks which practices should be prioritized. There is no defensible universal ranking independent of soil, water regime, management history and economic feasibility. On existing mineral-soil plantations, returning organic residues, protecting soil with managed vegetation, reducing damaging disturbance and optimizing fertilizer delivery are plausible first candidates. Their value is supported by oil palm-specific investigations of empty fruit bunches, management intensity, and understory relationships, supplemented by broader conservation-agriculture evidence (Noirot et al., 2022; Hennings et al., 2022; Thoumazeau et al., 2024). Wider analyses of ecological restoration and forest conversion show that greenhouse gas and soil responses vary significantly by ecosystem and intervention type, challenging one-size-fits-all sustainability formulas (He et al., 2024; Wang et al., 2021). The Brazilian oil palm agroforestry comparison by Gomes et al. (2024) adds a relevant qualification: improvements in surface soil chemistry and biological indicators were not accompanied by uniformly better physical soil condition. Meta-analyses of conservation practices and ecological restoration suggest that outcomes differ by initial soil conditions and climate, while some soil fractions respond more slowly than total SOC (Das et al., 2022; Pan et al., 2025). Future plantation trials should compare plausible combinations of interventions and measure carbon fractions, yields, soil physical condition, and gases concurrently.

4. Peatland Intervention Pathways Require Distinct Policy Treatment

The sixth research question requires a separate answer for peat. On deeply drained peat, increasing organic residue inputs cannot be assumed to offset decomposition of the underlying peat body. Evidence on tropical peat conversion, successive plantations and hydrological controls therefore supports a distinct decision pathway that begins with avoiding further drainage and protecting remaining natural peat ecosystems (Cooper et al., 2020; McCalmont et al., 2021; Ratai et al., 2024).

Rewetting is promising but it is not a semantic shortcut to declaring a plantation carbon neutral. Comparative peatland studies show that methane responses can complicate short-term totals even where CO_2 losses are reduced (Günther et al., 2020; Novita et al., 2024).

5. A Minimum Viable Measurement, Reporting, and Verification System

The seventh research question can be operationalized through a staged MRV architecture. Demonstrating a measured stock gain is not by itself sufficient to establish that the gain was additional to business as usual, was not created by displacement of emissions elsewhere, and will persist for the required duration. Critical work on crediting projects and impermanent carbon highlights the danger of assuming that reported issuance equals realized long-term atmospheric benefit (Probst et al., 2024; Balmford et al., 2023). For longitudinal assessment, the annualized change in equivalent-soil-mass-adjusted stock can be reported as the difference between observations divided by the elapsed time. An illustrative expression is:

$$\textit{Annual SOC change } (Mg\ C\ ha^{-1}\ yr^{-1}) = [SOC_{(}ESM,t_{2)} - SOC_{(}ESM,t_{1)}] / (t_2 - t_1)$$

The two stock observations must refer to the same reference soil mass and a compatible sampling design, with time expressed in years. Shared field protocols, registered sampling locations and transparent model versions can improve comparability between estates and smallholders (Danylo et al., 2021; Wong et al., 2023). Table 3 provides an operational data checklist for an estate or smallholder-focused MRV pilot.

Table 3. Proposed Monitoring, Reporting and Verification Data Specification

MRV component	Routine data	Additional requirements for removal claims
Baseline	Land-use map, age, soil class	Counterfactual and conversion history
Soil measurements	Depth, SOC, density, GPS locations	Replicated equivalent soil-mass change
Spatial information	Satellite/drone and management zones	Calibrated uncertainty and traceability
Gas / water	Input, fertilizer, peat water table	CO_2 / CH_4 / N_2O where relevant
Change attribution	Managed-versus-comparison blocks	Additionality, leakage and permanence
Reporting	Methods, site strata, confidence limits	Independent assurance and reversal rules

Table 3 provides a practical minimum-data specification for management reporting and higher-stakes climate claims. Peat hydrological indicators remain mandatory whenever the claim concerns drained or rewetted organic soils.

6. Governance, Distributional Justice, and a Phased Implementation Roadmap

The eighth research question moves from science to institutions. Indonesia can make meaningful progress by aligning oil palm intensification on existing suitable land with credible forest and peatland safeguards, consistent soil monitoring and better smallholder access to inputs and technical services. Carbon-credit revenue should be viewed as a possible supplementary instrument, not the sole business model for regenerative adoption. A combined incentive system could reward verifiable soil-cover practices, improved nutrient efficiency and habitat protection while reserving carbon removal claims for projects that clear a stricter additionality and permanence test.

Figure 4 translates the synthesis into a safeguards-first implementation roadmap. Each phase contains a decision gate that must be satisfied before claims or interventions are expanded.



Figure 4. Phased and Conditional Roadmap for Soil Carbon Stewardship in Existing Oil Palm Landscapes. Conceptual Diagram Developed for this Review

Figure 4 proposes a staged roadmap from protecting high-integrity ecosystems through establishing measurement baselines to scaling tested regenerative practices and independently assuring advanced carbon claims. Its sequencing is not a prediction that every farm will become carbon positive. Research on restoration and agroforestry supports experimentation with habitat enrichment; research on credit integrity favors independent scrutiny and long-term liability arrangements (Montoya-Sánchez et al., 2023; Ahirwal et al., 2022; Probst et al., 2024).

7. An Integrated Decision Matrix and Future Research Agenda

The proposed framework yields different decisions for different site conditions. On an existing mineral-soil estate with degraded inter-rows, soil-cover and residue-recycling trials are plausible, coupled with depth-resolved stock measurement. On a plantation abutting intact forest, conversion avoidance and buffer protection are prior obligations even if the plantation reports favorable operational fluxes. On drained peat, water-table control and restoration potential warrant urgent assessment independent of claims about canopy photosynthesis. The resulting landscape management problem is multidimensional rather than reducible to a carbon-only ranking (Meijaard et al., 2020; Zemp et al., 2023). Studies of mineral-associated organic matter, microbial pathways and climate-induced carbon vulnerability indicate why persistence must be investigated explicitly rather than inferred from a short-term increase (Elias et al., 2024; McFarlane et al., 2024; Tian et al., 2024). Table 4 maps the research questions to provisional answers and evidence gaps.

Table 4. Research-Question Synthesis and Remaining Uncertainty Matrix

Research question	Qualified synthesis	Priority evidence gap
RQ1: Carbon concepts	Annual NPP is not net climate removal	Harmonized rotation-level budgets
RQ2: Depth / age	Age patterns vary by soil and management	Repeated equivalent-soil-mass studies
RQ3: Baselines	Avoided conversion is crucial	Site-specific historical benchmarks
RQ4: Mechanisms	Minerals and microbes determine persistence	Oil palm root-to-MAOC pathways
RQ5: Management	Residue and cover show conditional promise	Replicated factorial estate trials
RQ6: Peat	Hydrology and oxidation dominate	Long-term rewetting GHG outcomes
RQ7: MRV	Field-lab-remote integration is essential	Affordable audit-grade protocols
RQ8: Governance	Smallholder viability affects adoption	Distributional and policy evaluations

Table 4 links the research questions to the proposed resolution, the most serious residual uncertainty and an implementation priority.

CONCLUSIONS AND RECOMMENDATIONS

Soil carbon stewardship provides an important opportunity to improve the sustainability of existing oil palm plantations, but it must not be equated with the photosynthetic productivity of the crop or treated as automatic evidence of climate neutrality. The literature supports several credible propositions: plantation age and management influence carbon fluxes; organic residues, roots, vegetation cover and microbial–mineral interactions can alter soil carbon dynamics; peatland drainage creates distinctive long-term risks; and biodiversity-oriented restoration can improve ecological functions in cultivated landscapes. None of these propositions, taken individually, establishes that conversion of carbon-rich forest or peat ecosystems to oil palm produces a net climatic gain. Darker soil profiles observed under repeated plantation generations are useful hypotheses for investigating deep carbon inputs, but measured sequestration requires baseline control, replicated depth-resolved sampling, bulk-density correction, equivalent-soil-mass comparison and long-term follow-up. The appropriate objective is persistent and additional soil carbon gain, evaluated in the context of other greenhouse gases, ecological integrity and the historical land-use baseline.

Mineral soils and organic peat should be treated through separate scientific and policy pathways because their carbon-storage mechanisms and principal risks are fundamentally different. Indonesia's most credible roadmap combines the protection of remaining high-carbon ecosystems with continuous improvement on existing plantations, better soil and water management,

representative long-term monitoring and transparent reporting. For producers, targeted residue recycling, suitable understory cover, reduced disturbance and appropriate nutritional management warrant local trials that jointly measure carbon, yield and other ecosystem benefits. For public institutions and certification systems, spatially explicit baselines, conservative attribution, independent assurance and smallholder-inclusive implementation are essential. The resulting recommendation is a shift from claims of inherent oil palm carbon sequestration toward a verifiable, site-specific model of carbon stewardship. Such a transition offers a more scientifically defensible and socially durable basis for regenerative oil palm sustainability.

FURTHER STUDY

This research still has limitations, so further studies are needed on the topic Beneath the Canopy: Rethinking Soil Carbon Sequestration, Greenhouse Gas Balances, and Regenerative Sustainability in Indonesia's Oil Palm Plantations to improve this study and provide more insights for the author and readers.

REFERENCES

Ahirwal, J., Sahoo, U.K., Thangjam, U. and Thong, P. (2022) "Oil palm agroforestry enhances crop yield and ecosystem carbon stock in northeast India: Implications for the United Nations sustainable development goals", Sustainable Production and Consumption, 30, pp. 478–487. https://doi.org/10.1016/j.spc.2021.12.022

Balmford, A. et al. (2023) "Realizing the social value of impermanent carbon credits", Nature Climate Change, 13, pp. 1172–1178. https://doi.org/10.1038/s41558-023-01815-0

Bicknell, J.E. et al. (2023) "Enhancing the ecological value of oil palm agriculture through set-asides", Nature Sustainability, 6, pp. 513–525. https://doi.org/10.1038/s41893-022-01049-6

Black, H.I.J. et al. (2022) "What makes an operational farm soil carbon code? Insights from a global comparison of existing soil carbon codes using a structured analytical framework", Carbon Management, 13(1), pp. 554–580. https://doi.org/10.1080/17583004.2022.2135459

Bohoussou, Y.N. et al. (2022) "Impacts of the components of conservation agriculture on soil organic carbon and total nitrogen storage: A global meta-analysis", Science of the Total Environment, 842, 156822. https://doi.org/10.1016/j.scitotenv.2022.156822

Camenzind, T. et al. (2023) "Formation of necromass-derived soil organic carbon determined by microbial death pathways", Nature Geoscience, 16, pp. 115–122. https://doi.org/10.1038/s41561-022-01100-3

Cooper, H.V. et al. (2020) "Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation", Nature Communications, 11, 407. https://doi.org/10.1038/s41467-020-14298-w

Danylo, O. et al. (2021) "A map of the extent and year of detection of oil palm plantations in Indonesia, Malaysia and Thailand", Scientific Data, 8, 96. https://doi.org/10.1038/s41597-021-00867-1

Das, S., Chatterjee, S. and Rajbanshi, J. (2022) "Responses of soil organic carbon to conservation practices including climate-smart agriculture in tropical and subtropical regions: A meta-analysis", Science of the Total Environment, 805, 150428. https://doi.org/10.1016/j.scitotenv.2021.150428

Dietz, C.L., Jackson, R.D., Ruark, M.D. and Sanford, G.R. (2024) "Soil carbon maintained by perennial grasslands over 30 years but lost in field crop systems in a temperate Mollisol", Communications Earth & Environment, 5, 360. https://doi.org/10.1038/s43247-024-01500-w

Dynarski, K.A., Kandanool, D., Adeleke, E., Veum, K.S., Carter, T.L. and Wills, S. (2026) 'Comparison of equivalent soil mass methods for soil organic carbon stock calculations', Geoderma, 474, 118053. https://doi.org/10.1016/j.geoderma.2026.118053

Elias, D.M.O. et al. (2024) "Microbial and mineral interactions decouple litter quality from soil organic matter formation", Nature Communications, 15, 10063. https://doi.org/10.1038/s41467-024-54446-0

Georgiou, K. et al. (2022) "Global stocks and capacity of mineral-associated soil organic carbon", Nature Communications, 13, 3797. https://doi.org/10.1038/s41467-022-31540-9

Golicz, K. et al. (2025) "The older, the better: a comprehensive survey of soil organic carbon under commercial oil palm plantations", Environmental Monitoring and Assessment, 197, 86. https://doi.org/10.1007/s10661-024-13540-y

Gomes, M.F. et al. (2024) 'Soil health indicators in oil palm agroforestry systems in the eastern Amazon, Brazil', Geoderma Regional, 37, e00806. https://doi.org/10.1016/j.geodrs.2024.e00806

Gomez, F. et al. (2024) "A dataset for soil organic carbon in agricultural systems for the Southeast Asia region", Scientific Data, 11, 374. https://doi.org/10.1038/s41597-024-03213-3

Grabs, J. and Garrett, R.D. (2023) "Goal-based private sustainability governance and its paradoxes in the Indonesian palm oil sector", Journal of Business Ethics, 188, pp. 467–507. https://doi.org/10.1007/s10551-023-05377-1

Günther, A. et al. (2020) "Prompt rewetting of drained peatlands reduces climate warming despite methane emissions", Nature Communications, 11, 1644. https://doi.org/10.1038/s41467-020-15499-z

He, T. et al. (2024) "Meta-analysis shows the impacts of ecological restoration on greenhouse gas emissions", Nature Communications, 15, 2668. https://doi.org/10.1038/s41467-024-46991-5

Hennings, N. et al. (2022) "Management extensification in oil palm plantations reduces SOC decomposition", Soil Biology and Biochemistry, 165, 108535. https://doi.org/10.1016/j.soilbio.2021.108535

Hergoualc'h, K., López Gonzales, M., Málaga, N. and Martius, C. (2025) 'Conversion of degraded forests to oil palm plantations in the Peruvian Amazonia: Shifts in soil and ecosystem-level greenhouse gas fluxes', Agriculture, Ecosystems & Environment, 386, 109603. https://doi.org/10.1016/j.agee.2025.109603

Jian, J., Du, X., Reiter, M.S. and Stewart, R.D. (2020) "A meta-analysis of global cropland soil carbon changes due to cover cropping", Soil Biology and Biochemistry, 143, 107735. https://doi.org/10.1016/j.soilbio.2020.107735

Kasak, K. et al. (2025) 'Greenhouse gas emissions from ditches in oil palm plantations on tropical peatlands in Malaysia', Scientific Reports, 15, 37126. https://doi.org/10.1038/s41598-025-21094-3

Liang, G., Stark, J. and Waring, B.G. (2023) "Mineral reactivity determines root effects on soil organic carbon", Nature Communications, 14, 4962. https://doi.org/10.1038/s41467-023-40768-y

Ling, J. et al. (2025) 'Soil organic carbon thresholds control fertilizer effects on carbon accrual in croplands worldwide', Nature Communications, 16, 3009. https://doi.org/10.1038/s41467-025-57981-6

McCalmont, J. et al. (2021) "Short- and long-term carbon emissions from oil palm plantations converted from logged tropical peat swamp forest", Global Change Biology, 27(11), pp. 2361–2376. https://doi.org/10.1111/gcb.15544

McCalmont, J. et al. (2023) "Oil palm (Elaeis guineensis) plantation on tropical peatland in South East Asia: Photosynthetic response to soil drainage level for mitigation of soil carbon emissions", Science of the Total Environment, 858, 159356. https://doi.org/10.1016/j.scitotenv.2022.159356

McFarlane, K.J. et al. (2024) "Experimental warming and drying increase older carbon contributions to soil respiration in lowland tropical forests", Nature Communications, 15, 7084. https://doi.org/10.1038/s41467-024-51422-6

Meijaard, E. et al. (2020) "The environmental impacts of palm oil in context", Nature Plants, 6, pp. 1418–1426. https://doi.org/10.1038/s41477-020-00813-w

Meijide, A. et al. (2020) "Measured greenhouse gas budgets challenge emission savings from palm-oil biodiesel", Nature Communications, 11, 1089. https://doi.org/10.1038/s41467-020-14852-6

Montoya-Sánchez, V. et al. (2023) "Landscape heterogeneity and soil biota are central to multi-taxa diversity for oil palm landscape restoration", Communications Earth & Environment, 4, 209. https://doi.org/10.1038/s43247-023-00875-6

Monzon, J.P. et al. (2023) "Agronomy explains large yield gaps in smallholder oil palm fields", Agricultural Systems, 210, 103689. https://doi.org/10.1016/j.agsy.2023.103689

Mulyanto, B. (2026) 'Soil carbon and sustainable oil palm plantation'. Unpublished presentation, as initial discussion material.

Murphy, D.J. (2024) "Carbon sequestration by tropical trees and crops: A case study of oil palm", Agriculture, 14(7), 1133. https://doi.org/10.3390/agriculture14071133

Noirot, L.M. et al. (2022) "Impacts of empty fruit bunch applications on soil organic carbon in an industrial oil palm plantation", Journal of Environmental Management, 317, 115373. https://doi.org/10.1016/j.jenvman.2022.115373

Noon, M.L. et al. (2022) "Mapping the irrecoverable carbon in Earth's ecosystems", Nature Sustainability, 5, pp. 37–46. https://doi.org/10.1038/s41893-021-00803-6

Novita, N. et al. (2024) "Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands", Science of the Total Environment, 952, 175829. https://doi.org/10.1016/j.scitotenv.2024.175829

Pan, J. et al. (2025) "Soil organic carbon fractions response to ecological restoration: A global meta-analysis", Ecological Engineering, 217, 107661. https://doi.org/10.1016/j.ecoleng.2025.107661

Paul, C. et al. (2023) "Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation?", Journal of Environmental Management, 330, 117142. https://doi.org/10.1016/j.jenvman.2022.117142

Peng, Y., Chahal, I., Hooker, D.C. and Van Eerd, L.L. (2024) 'Comparison of equivalent soil mass approaches to estimate soil organic carbon stocks under long-term tillage', Soil and Tillage Research, 238, 106021. https://doi.org/10.1016/j.still.2024.106021

Petri, H. et al. (2024) "Replanting challenges among Indonesian oil palm smallholders: A narrative review", Environment, Development and Sustainability, 26, pp. 19351–19367. https://doi.org/10.1007/s10668-023-03527-z

Prananto, J.A. et al. (2020) "Drainage increases CO2 and N2O emissions from tropical peat soils", Global Change Biology, 26, pp. 4583–4600. https://doi.org/10.1111/gcb.15147

Probst, B.S. et al. (2024) "Systematic assessment of the achieved emission reductions of carbon crediting projects", Nature Communications, 15, 9562. https://doi.org/10.1038/s41467-024-53645-z

Quezada, J.C. et al. (2022) "Deforestation-free land-use change and organic matter-centered management improve the C footprint of oil palm expansion", Global Change Biology, 28, pp. 2476–2490. https://doi.org/10.1111/gcb.16069

Rahman, N. et al. (2021) "The effects of management practices on soil organic carbon stocks of oil palm plantations in Sumatra, Indonesia", Journal of Environmental Management, 278, 111446. https://doi.org/10.1016/j.jenvman.2020.111446

Ratai, J. et al. (2024) "Tropical peat soil changes across successive oil palm generations in Sarawak, Malaysia", Heliyon, 10(18), e37754. https://doi.org/10.1016/j.heliyon.2024.e37754

Sasmito, S.D. et al. (2025) "Half of land use carbon emissions in Southeast Asia can be mitigated through peat swamp forest and mangrove conservation and restoration", Nature Communications, 16, 740. https://doi.org/10.1038/s41467-025-55892-0

Shabtai, I.A. et al. (2023) "Calcium promotes persistent soil organic matter by altering microbial transformation of plant litter", Nature Communications, 14, 6609. https://doi.org/10.1038/s41467-023-42291-6

Supriatna, J. et al. (2024) "Sustainability analysis of smallholder oil palm plantations in several provinces in Indonesia", Sustainability, 16(11), 4383. https://doi.org/10.3390/su16114383

Tadiello, T. et al. (2023) "Soil organic carbon under conservation agriculture in Mediterranean and humid subtropical climates: Global meta-analysis", European Journal of Soil Science, 74(1), e13338. https://doi.org/10.1111/ejss.13338

Thoumazeau, A. et al. (2024) "Effects of fertilization practices and understory on soil health and oil palm performances in smallholdings: An Indonesian case study", Agricultural Systems, 213, 103802. https://doi.org/10.1016/j.agsy.2023.103802

Tian, J. et al. (2024) "Microbially mediated mechanisms underlie soil carbon accrual by conservation agriculture under decade-long warming", Nature Communications, 15, 377. https://doi.org/10.1038/s41467-023-44647-4

Wang, Y. et al. (2021) "Forest conversion to plantations: A meta-analysis of consequences for soil and microbial properties and functions", Global Change Biology, 27(21), pp. 5643–5656. https://doi.org/10.1111/gcb.15835

Wells, J.M. et al. (2022) "Edaphic controls of soil organic carbon in tropical agricultural landscapes", Scientific Reports, 12, 21574. https://doi.org/10.1038/s41598-022-24655-y

Wong, Y.B. et al. (2023) "Smallholder oil palm plantation sustainability assessment using multi-criteria analysis and unmanned aerial vehicles", Environmental Monitoring and Assessment, 195, 577. https://doi.org/10.1007/s10661-023-11113-z

Xu, Y. et al. (2022) "Recent expansion of oil palm plantations into carbon-rich forests", Nature Sustainability, 5, pp. 574–577. https://doi.org/10.1038/s41893-022-00872-1

Zemp, D.C. et al. (2023) "Tree islands enhance biodiversity and functioning in oil palm landscapes", Nature, 618, pp. 316–321. https://doi.org/10.1038/s41586-023-06086-5

Zhou, Z. et al. (2024) "Global turnover of soil mineral-associated and particulate organic carbon", Nature Communications, 15, 5329. https://doi.org/10.1038/s41467-024-49743-7