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Beyond Carbon Stocks: Integrating Field Flux Measurements, Land-Use Histories, and Life-Cycle Evidence for Climate-Integrity Accounting in Oil Palm Systems

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Abstract

Background: Carbon sequestration claims in oil-palm production frequently combine standing biomass inventories, soil measurements, local greenhouse-gas fluxes and product life-cycle estimates without comparable boundaries. Objective: This review evaluates the evidence required to distinguish carbon storage from a net atmospheric sink or verifiable climate-mitigation contribution.

Methods: A critical qualitative literature review synthesises fifty-nine peer-reviewed journal articles published from 2020 through 2026, using a Central Kalimantan field briefing as a problem-setting case.

Results: Six themes emerge: carbon-pool comparability; land-use history and peat drainage; multi-gas fluxes; complementary measurement systems; management interventions; and baseline and verification integrity. The briefing illustrates a consequential mismatch between forest biomass-only values and plantation vegetation-plus-soil totals. High-frequency sensor transmission similarly does not independently establish accurate annual emissions.

Contribution: A six-stage Carbon Integrity Ladder links matched inventories, temporal changes, flux closure, land-use counterfactuals, life-cycle and uncertainty reconciliation, and independent governance.

Conclusion: Credible oil-palm mitigation begins with avoiding forest and peat conversion, followed by verified reductions on existing land; individual stock measurements cannot substantiate a net-carbon-sink claim.

Keywords: Oil Palm, Carbon Stocks, Greenhouse-gas Fluxes, Land-Use Change, Tropical Peatlands, Soil Organic Carbon, Eddy Covariance, Monitoring, Reporting and Verification, Life-Cycle Assessment, Carbon-Credit Integrity.

Introduction

A Climate Accounting Problem Disguised as a Vegetation Problem

Oil palm is simultaneously a productive perennial crop, a major component of tropical agricultural landscapes, and an unusually contested object of climate accounting. Its canopy, trunks, fronds, roots and managed understory contain measurable carbon, while its fruit provides vegetable oil at a land-use efficiency that makes simple comparisons with alternative oil crops difficult. Yet a measurement of standing biomass answers a different question from whether an estate has reduced atmospheric greenhouse gas concentrations relative to a plausible alternative landscape. This distinction has become central to the credibility of corporate net-zero commitments, deforestation-free supply chains and land-based climate claims. Recent spatial assessments document oil palm expansion into carbon-rich forests, while analyses of changing forest and peatland uses show why land-conversion history cannot be omitted from the climate account [1-4].

The foundational distinction is between a carbon stock, a rate of carbon accumulation and a net carbon sink. A stock, commonly expressed in tonnes of carbon per hectare, describes carbon present at a specified time and within specified compartments. A sequestration rate expresses a change in stored carbon over an interval, but the change can be reversed by harvest, fire, decay, replanting or drainage. A net atmospheric sink requires a defined balance between removals and releases over space and time; whether it means net carbon dioxide exchange or net climate impact depends on the gases and processes included. Reviews of terrestrial carbon sinks and soil-climate strategies caution that storage potential is conditional, spatially heterogeneous and sensitive to disturbance [5-8]. This review is motivated by an eleven-slide field and teaching briefing prepared in 2026 titled 'Climate Change Mitigation in Oil Palm Production: Carbon Storage and Field Measurements', prepared by Valensi Kautsar at INSTIPER Yogyakarta. The briefing accurately draws attention to

the non-equivalence of a carbon stock and a net sink; it illustrates plantation age classes, soil pools, field chambers and a high-frequency monitoring dashboard. It also reports illustrative field carbon densities in Central Kalimantan. These are treated here as preliminary source claims and research-design prompts, not as independently audited measurements or as grounds for extrapolation across Indonesia. The central scientific opportunity is to transform those fragments into a coherent, boundary-explicit and testable interpretation of oil-palm climate performance.

Why Spatial, Temporal and Methodological Boundaries Matter

A mature plantation may exchange carbon dioxide with the atmosphere in a manner resembling an ecosystem-scale sink during a particular observation year, while its establishment may have incurred a much larger one-off emissions burden through forest clearing or peat drainage. At another scale, a mill may cut methane releases by installing capture equipment without increasing the carbon contained in the crop or soil. Reduced emissions intensity per tonne of crude palm oil can therefore coexist with higher absolute emissions if production or land conversion expands. Research measuring greenhouse gas balances directly and studies of palm-oil life cycles demonstrate the danger of transferring conclusions from one accounting boundary to another without adjustment [9-13]. Differences between mineral soils and drained peatlands sharpen this problem. On mineral land, changes in aboveground biomass, soil management and fertiliser-related nitrous oxide may dominate particular reporting categories. On peat, drainage, aerobic decomposition, subsidence, fire risk and altered hydrology introduce large and persistent carbon losses that need not track the rise in palm biomass. A single average emission factor or a single snapshot of aboveground carbon is poorly suited to these distinct biophysical systems. Empirical studies from Southeast Asian peatlands and Borneo show how site history, drainage and emissions measurement change the size and interpretation of a climate balance [15-18].

The mismatch also concerns observation methods. Tree inventories and allometric equations estimate standing living carbon. Soil coring estimates a stock conditional on sample depth, fine-earth mass and laboratory analysis. Eddy covariance observes turbulent exchange over a changing footprint, whereas a chamber samples a small soil or surface area over a short interval; fertiliser, wet-season and drainage events can defeat sparse sampling schedules. Automated sensors can increase temporal resolution but cannot on their own correct spatial bias, wrong units, calibration drift or absent source measurements. Several recent technical papers demonstrate that chamber closure duration, soil-mass normalization and field-scale modelling remain consequential sources of uncertainty [19-23].

Objectives, Questions and Original Contribution

The study asks which evidence would justify describing an oil-palm estate as a carbon store, a sequestration pathway, a net carbon-dioxide sink or a genuine net greenhouse-gas mitigation intervention. It examines how land-use history, soil type, plantation age and management shape the answer; how field, remote and accounting methods can be reconciled; and how operational improvements can be distinguished from additional, durable and verifiable climate benefits. The guiding objective is not to replace one disputed number with another, but to set out the minimum evidentiary conditions for defensible statements. That orientation is particularly relevant to Indonesia, where large industrial estates, diverse smallholders and ecologically sensitive forest-peat mosaics coexist [24-28]. Figure 1 introduces the proposed accounting logic by positioning the previous landscape, present ecosystem and operational product system as three interdependent evidentiary domains. The figure is a conceptual synthesis prepared for this review, not an empirical result; its arrows describe required accounting connections rather than causal effects estimated from one dataset. By design, it prevents the visual prominence of stored palm biomass from masking pre-conversion losses or emissions beyond the field boundary. It also situates verification and uncertainty after, rather than before, the relevant accounting boundaries have been established.

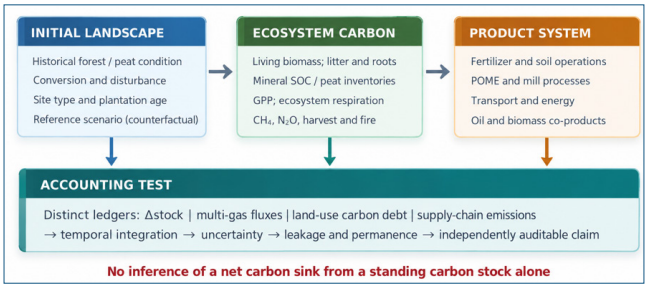


Figure 1: Boundary-First Climate-Integrity Accounting Linking Prior Land-Use History, Measured Ecosystem Carbon and Greenhouse-Gas Fluxes, and the Product System. Each Domain Must Be Evaluated Using Compatible Accounting Boundaries Before a Mitigation Claim Can Be Made; this is An Author-Developed Conceptual Synthesis.

A crucial implication of Figure 1 is that there is no universal conversion from a positive carbon-stock measurement into a justified net-zero claim. A defensible assessment must first determine what was present before conversion, what is currently retained, which gases are emitted or removed, and what would probably happen without the intervention. It must then specify the reporting period, distinguish site-level from product-level assertions, and prevent the same reduction from being claimed twice. This boundary-first approach provides the conceptual foundation for the rest of the review and aligns the examination of biophysical evidence with current concerns about crediting additionality and baseline choice [27-29].

Literature Review: Biophysical and Accounting Foundations Carbon Stocks, Ecosystem Fluxes and Genuinely Comparable Quantities

The elementary accounting identity is that a stock change over a defined interval equals inputs minus outputs plus transfers across the chosen boundary. In terrestrial ecosystems, gross primary production describes photosynthetic carbon fixation; ecosystem respiration includes autotrophic and heterotrophic releases. Net ecosystem exchange, net ecosystem production and net biome carbon balance are related but non-identical because their conventional sign systems and inclusion of harvest, dissolved export and disturbance pathways differ. Papers claiming that an agricultural ecosystem is a sink must state both the mathematical sign convention and the included carbon transfers. The broader terrestrial literature shows that changes in atmospheric forcing, climate variability and land management can all affect observed sinks, even when vegetation area is unchanged [7,8,30]. Four quantities require distinct mathematical treatment. A repeated inventory measures a change in the same carbon pool, whereas eddy-covariance studies commonly define net ecosystem exchange (NEE) as ecosystem respiration minus gross primary production

(GPP), with positive CO_2 exchange indicating a release to the atmosphere. The stock and flux equations below use explicitly identified boundaries and cannot be interchanged merely because both may eventually be expressed per hectare [12,31].

$$\Delta C(\text{pool}; t_1,t_2) = C(\text{pool}; t_2) - C(\text{pool}; t_1) \quad (1)$$

$$NEE(CO_2) = R(\text{ecosystem}) - GPP \quad (2)$$

In Equation (1), the two stocks must refer to identical compartments, area, soil-mass basis and comparable measurement protocols, and division by the elapsed years is needed to express an average stock-change rate. Equation (2) adopts the atmosphere-positive NEE convention; a negative value therefore indicates net CO_2 uptake during the observation period but does not by itself establish net ecosystem carbon accumulation after harvesting, lateral export or disturbance. Those additional transfers, and the independently quantified fluxes of methane and nitrous oxide, must be handled in further ledgers instead of being silently subsumed into NEE [12,31]. Aboveground palm stems and fronds, belowground living roots, understory vegetation, dead organic material and soils represent different physical reservoirs. Their turnover differs: harvested fresh-fruit bunches rapidly leave the field, pruned fronds decompose within managed rows, woody stems accumulate over a crop cycle, and certain soil fractions may persist considerably longer. A stock survey restricted to living vegetation omits soils and dead matter; conversely, a reported 'ecosystem stock' is not complete if deeper soil or belowground biomass is excluded without explanation. Palm agroforestry and conservation set-aside studies show that woody companions and remnant patches may influence local carbon storage and biodiversity, but their ecological contribution should not be used to erase the separate accounting of former forest losses [32-35]. A practical risk is comparing two measurements solely because their units match. Both a forest aboveground-biomass estimate and a plantation vegetation-plus-soil estimate can be given in tonnes C per hectare, yet the numerical difference cannot be interpreted as an ecosystem carbon difference when the included components are unequal. Comparable calculations require matched compartments, land extent, soil depth, sampling design, carbon fractions and accounting year. Forest deep-soil carbon studies underscore the magnitude of error possible when the soil depth or the treated pool changes between reference and intervention areas. This requirement is especially important when an attractive figure presents forests and palm stands side by side without stating which compartments exist beneath each bar [19,36-38].

Soil Carbon: Management, Measurement and the Limits of Accumulation Narratives

Soils hold a large global organic carbon reservoir, making even moderate regional changes potentially meaningful for climate mitigation. However, the well-known four-per-thousand aspiration should be read as a policy-oriented benchmark rather than a universally attainable annual addition of 0.4% to every soil carbon stock. Input availability, mineral association, temperature, moisture, depth, prior management and saturation can constrain accumulation, while disturbance can return previously retained carbon to the atmosphere. Analyses of soil as a natural climate solution emphasize local environmental limits, trade-offs and the need to separate measured stock changes from assumed potentials [5-7,30]. Soil sampling presents a particularly difficult comparison problem because land use alters bulk density, compaction and the distribution of fine-earth mass with depth. Two samples taken to a fixed depth may represent different masses of mineral soil, confounding carbon stock comparisons. Equivalent-soil-mass procedures can improve inference under some conditions, but they are not error-free and require careful implementation, especially when soil profiles and sampling layers differ. Recent methodological comparisons recommend transparent reporting of bulk density, coarse fragments, sampled intervals, interpolation and detectable-change uncertainty rather than reliance on a single correction formula [19,20,37,39,40].

In oil palm, soil carbon responds to both prior land use and highly heterogeneous current management. Organic matter may accumulate in frond piles and under managed ground cover but differ substantially in harvested paths, bare circles and machinery tracks. Management studies in Sumatra identify divergent soil carbon stocks across fertiliser and residue treatments, while newer surveys argue against treating stand age as the only explanatory variable. A literature-based comparison should therefore report soil position, clay and hydrological context, fertilisation history, organic input patterns and stand age, rather than attributing all differences among plots to the palms themselves [41-43]. Techniques combining remote imagery and models promise landscape-wide soil carbon monitoring, but their apparent high resolution does not eliminate the need for stratified ground calibration. Spectral canopy signals are not direct measurements of carbon deep in mineral soil or tropical peat, and machine-learning outputs can be sensitive to training distribution and spatial autocorrelation. Emerging soil-monitoring research shows the potential of model-aided estimates alongside methodological questions about detecting small trends over short periods. The relevant lesson for oil-palm MRV is to treat map products as inference with validation requirements, not as replacements for soil cores, laboratory assays and hydrological observations [19,21,40,44].

Land-Use History, Forest Carbon Debt and Temporal Attribution

Any evaluation of plantation performance begins with its reference landscape. Replacing a previously cleared agricultural field, restoring a degraded site, and draining intact peat forest do not share a common climate baseline. In addition, the relevant counterfactual is not always a static forest that would remain unchanged indefinitely; it is an explicit, evidence-grounded scenario that considers realistic land-use trajectories and governance. The carbon debt incurred during conversion must be distinguished from the annual growing-stock increment within the resulting plantation, and any proposed repayment period depends on discounting assumptions, yield, management and the scope of emissions. Research on forest conversion and zero-deforestation pathways demonstrates how oversimplified baseline comparisons can create spurious mitigation credit [4,26,28,29]. Long-term peatland measurements strengthen the requirement for a historical boundary. A 12–15-year comparison of Indonesian peat-swamp forests found that drainage produced persistent CO_2 losses and that drought and smoke haze could shift an otherwise functioning forest sink towards an annual source. Radiocarbon analysis of disturbed peat in Central Kalimantan further showed that drainage and fire can release carbon accumulated centuries or millennia earlier, making simple short-cycle compensation narratives implausible. These observations concern peatland disturbance pathways and do not establish a universal emission factor for every oil-palm estate [45,46].

Chronology matters within the crop system itself. Young palms

typically possess less standing woody carbon than mature individuals, but annual photosynthetic uptake does not rise indefinitely with accumulated woody biomass. Harvest exports substantial carbon, replanting can release carbon from removed stems, and soil disturbance may coincide with each rotation. Some measured mineral-soil plantations exhibit an annual carbon dioxide sink over the monitored period, yet the sign of an instantaneous ecosystem exchange is not enough to establish a net climate benefit when past land conversion and life-cycle releases are incorporated. Directly measured oil-palm budgets provide an unusually clear empirical example of this temporal and boundary dependence [11,12,15]. On drained peatlands, the uncertainty is not merely a single conversion-date pulse. Oxidation and subsidence can persist for years or decades, while wildfire risk increases under particular climatic and hydrological conditions. Work in Borneo apportions carbon dioxide releases among land-use change, fire and oxidative peat decomposition, and field investigations report relationships among drainage, soil properties and greenhouse-gas emissions. Even a plantation whose aboveground carbon stock has risen relative to its first planting year may therefore continue to lose substantial previously stored soil carbon. Any credible claim of 'carbon neutrality' must be explicit about whether drainage-driven peat loss remains within its boundary [10,14,16,18].

Multigas Balances and Industrial Life Cycles

Carbon dioxide is not the sole greenhouse gas relevant to oil palm systems. Nitrous oxide can be produced following nitrogen additions and through soil processes dependent on moisture, aeration and microbial conditions; methane arises from anaerobic processes and wastewater decomposition, while some aerated soils may consume atmospheric methane. Palm oil mill effluent treatment, energy for milling, fossil fuels for transport and fertiliser production create additional sources outside the plant's photosynthetic account. Converting these gases to carbon-dioxide equivalents using a declared assessment horizon supports certain comparisons, but it should not obscure the different physical lifetimes and mitigation pathways of each gas. Field observations and life-cycle studies both demonstrate the consequences of ignoring these emissions [9,13,23,47,48]. An additional source often absent from simplified accounts is water moving through the plantation drainage network. Measurements in Sarawak identified methane emissions from ditches associated with oil-palm cultivation on tropical peat, while microbiological evidence from a forest-to-palm transition documented changing carbon- and nitrogen-cycling pathways alongside increased CO_2 and N_2O releases. Because the spatial coverage and hydrological conditions of ditches differ among estates, these findings call for stratified sampling of water bodies rather than indiscriminate application of a single factor. They also caution against treating methane measured at an effluent pond as representative of field drainage emissions [49-50].

Product-based life-cycle assessment (LCA) asks a different question from whether a hectare of estate land is a carbon sink. It may evaluate emissions per tonne of crude palm oil, per unit of edible oil or per unit of transport energy delivered as biodiesel, with different product allocations and use-phase assumptions. Corporate or industry improvements can lower an emission intensity while absolute landscape emissions remain substantial; changes in mill methane capture can change the product footprint without altering the plantation carbon stock. Comparisons across LCA studies require consistency in functional unit, land-use change treatment, mill co-product allocation, energy mix, fertiliser input, geographical representativeness and reporting period. Recent palm-industry analyses illustrate both the practical mitigation possibilities and the sensitivity to assessment choices [9,11,13,25,51].

Measurement Theory and the Governance of Carbon Claims

Forest and plantation inventories rely on plot design, tree dimensions, species or age-specific allometry and representative sampling. In oil palm, changing architecture and trunk characteristics with age complicate extrapolation from a small number of trees. Remote-sensing approaches based on optical data, radar and spaceborne lidar can map plantations and estimate aboveground biomass, but their outputs depend on canopy structure and training datasets. High-resolution maps distinguish some industrial and smallholder configurations, while hierarchical satellite biomass models require field-reference calibration and uncertainty estimates for the landscape to which they are transferred. Combining these instruments is promising precisely because none observes every carbon pool directly [1,2,21,36]. Field gas measurements have similarly distinct domains of validity. Eddy covariance quantifies turbulent net exchange within an evolving atmospheric footprint and is powerful for seasonal carbon-dioxide budgets, but its results depend on filtering, closure assumptions, weather and post-processing. Manual chambers allow carefully targeted comparisons of ground treatments, but their spatial coverage is small and sampling frequency may miss peaks after fertiliser additions or storms. Automated chambers improve the timing of local observations, yet cannot be interpreted as direct estate-wide emissions without a defensible spatial sampling and extrapolation model. Recent empirical and technical studies illustrate the importance of closure periods, high-frequency events and ecosystem-versus-soil measurement differences [12,22,23,48].

Sampling times can generate a systematic error even when an instrument is analytically precise. Automated and manual chamber comparisons in a mature oil-palm plantation on peat detected diurnal patterns in soil CO_2 efflux, implying that a campaign confined to one part of the day may bias an annual extrapolation. This is an observation about sampling design and environmental representativeness, not proof that automation eliminates error; the frequency, chamber closure and ambient conditions still require calibration and reporting. A well-designed MRV architecture should therefore disclose time-of-day coverage as well as the number of readings and the percentage retained after quality control [22,52]. Climate reporting adds a normative layer to measurement. A reduction compared with an estimated baseline is not automatically a removal from the atmosphere, and a counterfactual that overpredicts future deforestation can make apparently impressive credits meaningless. Additionality, durability, leakage, double claiming and safeguards become decisive when a result is sold or communicated as a climate contribution. Reviews of realized carbon-credit effectiveness and methodological evaluations of deforestation baselines indicate that measurement sophistication alone cannot remedy a weak accounting reference scenario. Credible MRV must therefore integrate technical accuracy with incentive design, documentation and independently reviewable assumptions [27-29,53].

Method: Critical Qualitative Literature Review

Review Design and Sources

The article employs a qualitative literature review (QLR), not a systematic literature review, systematic evidence map or quantitative meta-analysis. Its purpose is to clarify concepts,

interpret conflicting measurement results and build a coherent conceptual framework across biogeochemistry, plantation management, remote sensing, LCA and carbon-market governance. The starting artifact is the eleven-slide Kautsar teaching and field briefing, which is assessed for its conceptual framing, reported numbers and missing metadata. Peer-reviewed journal publications from 2020 through 2026 provide the external evidence for critical interpretation; the briefing's own statements are identified as source-reported observations, not promoted to the status of independently validated research findings. Evidence was assembled purposively around the causal and measurement questions raised by the briefing. The search strategy prioritized recent journal papers on oil palm conversion and carbon stocks; tropical peat and mineral-soil greenhouse-gas fluxes; soil sampling comparability; manual chambers and eddy covariance; satellite mapping and monitoring; LCA; and forest carbon integrity. Both direct oil-palm studies and carefully identified methodological papers from adjacent terrestrial systems were included where needed to explain soil equivalent-mass sampling, detection limits, greenhouse-gas methods or broader crediting risks. The revised bibliography contains fifty-nine peer-reviewed journal articles within the 2020–2026 window, each linked by its digital object identifier; these items were used to formulate the thematic analysis rather than listed as an unattached reading archive.

Analytical Coding, Contrast and Triangulation

The first coding dimension separated conceptual objects: stocks, rates, ecosystem fluxes, greenhouse-gas equivalents, product intensities, avoided emissions and durable removals. The second separated land contexts, including primary or degraded forest, mineral-soil plantations, peatland plantations, industrial estates, smallholders and restoration or conservation areas. The third recorded method, temporal extent and observational support, recognising that one soil chamber measurement, one-year tower record, repeated soil cores and a life-cycle model are not interchangeable. The fourth captured governance assumptions, including land-use baselines, additionality, leakage, long-term reversibility and reporting incentives. An interpretive comparison sought disagreements as actively as agreement. For example, an apparent annual carbon-dioxide sink reported for a mature mineral-land plantation is not treated as contradictory to evidence of long-term climate damage from deforesting peat; the studies address different ecosystems, time horizons and denominators. Likewise, a lower product carbon footprint resulting from a better effluent treatment system is not read as proof of net carbon removal. The purpose of thematic triangulation is to identify precisely which change in definition resolves an apparent conflict and where real empirical disagreement remains after those definitions are aligned [11,12,15,23].

Evaluation Criteria, Transparency and Limitations

The qualitative evidence assessment emphasized whether each claim made its system boundary explicit, observed relevant processes, described temporal and spatial representativeness, accounted for uncertainty and recognized plausible alternative explanations. Higher interpretive weight was given to field studies with measured fluxes or transparent multi-source inventories for claims about biophysical processes, while reviews and methodological articles informed measurement designs and governance evaluation. Reported numerical results were treated as site-specific and not pooled into a pseudo-national average. Because the approach is a purposive QLR rather than an SLR, it does not claim exhaustive database coverage, protocol registration, PRISMA screening statistics or formal study-level risk-of-bias scoring. There are corresponding limitations. The briefing presentation does not include raw instrument datasets, calibration certificates, precise plot coordinates, independent audit records or full methods for converting field samples into carbon stocks. It is therefore impossible to reanalyse the field figures or verify the stated dashboard continuity from the slides alone. The literature also contains different climate horizons and carbon-pool definitions, so the review cannot calculate a valid composite national emissions factor from heterogeneous estimates. Its deliverable is a theory-informed framework, transparent interpretation of available findings and a set of testable requirements for subsequent field research, rather than a new empirical estimate of Indonesian plantation emissions. External MRV demonstrations can inform implementation without being treated as validation of the Indonesian pilot. For example, a recent large-scale agricultural carbon-credit implementation combined field records, soil sampling, modelling, uncertainty deductions and leakage checks, offering a transferable description of quality-control stages rather than a transferable oil-palm emissions factor. Its experience highlights the difference between a working data pipeline and an independently defensible mitigation claim. Such analogical evidence is used here to identify verification requirements only, with geographical and methodological differences stated explicitly [54].

Results: Thematic Findings

Theme I: A Visible Carbon Stock is not A Complete Land-Use Carbon Budget

The literature reveals a consistent conceptual asymmetry between the quantities that are easiest to display and those that most strongly determine climate integrity. Standing tree biomass can be photographed, inventoried and repeatedly mapped, whereas soil organic carbon changes can be slower to detect and historical land conversion cannot be inferred from a contemporary canopy image alone. Forest soil carbon and peat deposits may be especially consequential precisely because they are hidden beneath the visible vegetation. A monitoring design focused on measuring palm trunks will therefore produce a technically valid estimate of a narrow carbon pool but not a landscape-scale greenhouse-gas account. Comparative forest-biomass mapping and deeper soil-carbon studies reinforce this interpretive limit [5,36,38]. Oil-palm canopy development also produces a predictable visual temptation. The immature stand appears relatively sparse, while older palms accumulate substantially more aboveground living material; when the sample is cross-sectional, an age gradient may resemble a time-series gain. However, different age classes may occupy soils with distinct pre-conversion histories, clay textures, drainage intensities or fertiliser schedules. Without a repeated-plot design or a credible age-controlled comparison, the gradient cannot establish annual sequestration. The empirical literature suggests that both age and management matter, with marked spatial differences across frond piles and other field micro-sites [41-43].

The source briefing offers a concrete illustration. Its Central Kalimantan slide reports 191.44 t C ha−1 for 'biomass carbon' in high-carbon-value forest and 41.84, 74.09 and 86.32 t C ha−1 for immature, prime-mature and older-mature palm stands respectively. The palm totals combine reported vegetation carbon and soil carbon, while the forest figure is explicitly labelled biomass carbon and lacks a separately reported soil term. For prime-mature palms, displayed components of 32.66 and 41.44 sum to 74.10 rather than the labelled 74.09, probably because of

rounding or an unreported precision convention. These are not evidence of numerical fraud; they are reasons to request calculation sheets, carbon pool descriptions and uncertainty values before interpreting apparent differences. The practical conclusion is that a graph of those four heights cannot be read as a valid comparison of total forest and plantation carbon. At a minimum, the forest soil pool must be measured to a compatible depth and soil mass, and the plantation soil and biomass estimates must use consistent inclusion rules. It would also be necessary to specify whether roots, dead organic matter, peat depth, understory carbon and carbon exported with harvest are within scope. The methodological literature on equivalent soil mass and deep soil carbon provides a feasible pathway to making these comparisons more defensible [19,20.,38,39].

Theme II: Site Type Governs the Sign and Persistence of Greenhouse-Gas Consequences

The contrast between peatland and mineral-soil plantations is one of the most consequential results of the literature synthesis. In peatlands, drainage can expose formerly waterlogged organic material to oxygen and thereby sustain carbon dioxide release independently of the annual gain in palm tissues. Conversion of peat swamp forest also removes pre-existing forest biomass, while peat fires can add large emissions when ignition and drought occur. Cooper and colleagues show the importance of the full greenhouse-gas implications of conversion, and peat plantation measurements illustrate why annual carbon exchange must not be assessed without peat decomposition. The broad policy implication is that safeguarding remaining forest peat represents a different category of intervention from improving an established plantation's operating efficiency [10,15,17,18]. Peat effects are nevertheless heterogeneous. Water-table depth, previous logging, peat thickness, fertiliser practice, microbial dynamics and plantation developmental stage influence flux magnitudes and uncertainty. Research connecting drainage status and photosynthetic response indicates that simple prescriptions to deepen or shallow drainage cannot be judged solely from aboveground crop growth, and studies of peat physicochemical properties report variability among land uses. Rewetting established plantations may reduce heterotrophic carbon releases, but the magnitude and feasibility of the benefit depend on agronomic and landscape hydrology. A documented reduction in one component of soil respiration must not be equated mechanically with a fully restored peat forest greenhouse-gas balance [14,16,55].

Mineral-soil systems require a different interpretation. There, reduced or enhanced ecosystem carbon uptake over a monitoring interval may change with palm age, water limitation, management and biomass growth. The directly measured budget reported by Meijide and colleagues demonstrates why short-term ecosystem exchange cannot be divorced from fossil inputs or previous land-use transitions when discussing emission savings. Forest replacement may also alter soil respiration and methane consumption even where deep organic peat is absent. A credible national synthesis must therefore stratify rather than collapse peat and mineral plantations into a single biophysical class [12,47,56]. Rotation-scale evidence from an Indonesian Acacia fibre-wood plantation offers a useful methodological contrast rather than direct oil-palm performance evidence. That peatland study integrated eddy-covariance fluxes, methane, soil nitrous oxide, dissolved and harvested carbon over a full rotation, showing the importance of reporting a complete balance across establishment and harvest. Its crop system and management cannot be transferred numerically to oil palm, but the scope of its measurement ledger illustrates what is missing from short-duration, aboveground-stock-based claims [31].

Theme III: A Complete Greenhouse-Gas Account Must Include Event-Driven N_2O and CH_4

Nitrous oxide is a conspicuous weakness in plantation accounts based only on carbon stock or carbon dioxide monitoring. Fertiliser applications, rain events, surface water conditions and changes in soil oxygen availability can create pulses that are poorly represented by occasional daytime chamber readings. Ecosystem-scale work in an Indonesian oil-palm plantation found materially different nitrous oxide estimates from eddy covariance and conventional soil chamber observations. The important lesson is not that one instrument is universally superior, but that a small soil-surface chamber and a landscape-scale flux footprint see different combinations of hotspots and processes. Extrapolation should be designed to reconcile those spatial and temporal differences rather than hide them [22,23]. Methane adds another contextual layer. Well-aerated soils may absorb methane, while periodically saturated soils, drainage structures and anaerobic mill waste can release it. Research tracking methane and nitrous oxide during peat forest-to-palm transitions demonstrates that seasonal variability and site-specific conditions complicate the interpretation of a handful of observations. Work examining replacement of natural forest by plantation also finds that soil-respiration and methane-flux changes can travel in different directions, showing why net climate accounting needs both gases. For palm mills, an effluent pond may dominate a specific methane-management opportunity but belongs to a different measurement domain from root-zone soil flux [11,47,48].

A central interpretive problem is denominator selection. A per-hectare annual N_2O or methane flux, a plant-specific chamber flux, a mill pond emission rate and emissions per tonne of oil cannot simply be added as published, even if they are all eventually expressed in CO_2e. Areas, processing throughput, gas mass flows, source durations, climate-equivalence conventions and shared system boundaries must first be reconciled. LCA research offers the accounting architecture for product comparisons, but its results remain sensitive to location, conversion assumptions and operational data. The literature therefore supports one integrated inventory with disaggregated source ledgers, not an informal sum of impressive-looking numbers [9,13,25,51]. Recent source-specific investigations reinforce the need to represent spatial and seasonal hotspots. Sampling of Sarawak peatland drainage ditches revealed methane efflux that would not be recovered from an inventory restricted to well-drained palm-circle soils. In a longitudinal forest-to-palm transition, measured gas changes occurred alongside shifts in water tables and microbial functions rather than as a constant response to fertiliser alone. Accordingly, a national or estate-scale account should partition field soils, canals, effluent ponds and combustion sources before aggregation, and should not assign the same chamber-based factor to all of them [49,50].

Theme IV: Measurement Frequency Improves Detection but not Necessarily Representativeness

The source briefing distinguishes greenhouse-gas calculators, eddy covariance, manual chambers and automated chambers, and further describes roughly ten-minute data transmissions for eight months from field, vehicle, wastewater and chimney monitoring. This suggests an ambitious pilot monitoring arrangement, but

the slides do not establish which analytical instruments were deployed for each source, which gases were measured, how the measured signals were converted to mass fluxes or what proportion of records passed quality assurance. A dashboard update interval is not the same as the duration of a gas measurement, and a maintained network connection is not evidence of measurement accuracy. A monitoring system should separately disclose sampling frequency, calibration frequency, uptime, usable-data coverage and spatial extrapolation methods. Each method can answer a defensible question once deployed within its technical domain. Manual chambers are valuable for replicated soil-treatment comparisons and for tracing micro-site variability, particularly with sampling intensified around fertiliser application and rainfall. Automated chambers provide denser local temporal coverage but still demand corrections for leakage, pressure disturbance, chamber closure and analyser drift. Eddy covariance may offer a more integrated ecosystem footprint, but that footprint shifts with atmospheric conditions and can include paths, drainage or neighbouring surfaces. Methodological work on chamber closure and ecosystem-scale N_2O fluxes demonstrates that monitoring upgrades require specific performance tests rather than generic declarations of 'real-time' accuracy [21-23].

Measurement sources at a mill or in transportation require equally careful engineering definitions. A chimney generally needs concentration measurements combined with verified stack volumetric flow and operating time; a wastewater pond needs a method that represents its variable exposed area, bubble ebullition and other emission routes. Vehicle activity can be estimated using fuel use, emission factors and operational logs, or measured by specialized equipment with suitable sampling protocols. The terminology 'automated chamber' cannot safely be applied to all these installations without specifying their physical sampling interface. Lifecycle assessment and digital supply-chain reporting research help organize such sources, but do not excuse missing instrument metadata [11,25,51]. Figure 2 translates this evidence into a practical monitoring, reporting and verification architecture. It shows why inventories, gas fluxes, satellite observations and operational records should enter a common evidence pipeline only after their own validity checks and their relationships have been documented. The final verification stage requires an uncertainty interval and a claim-specific baseline, not merely a colorful digital dashboard. The components are recommendations assembled through qualitative synthesis, rather than a description of software capabilities verified at the field site in the briefing.

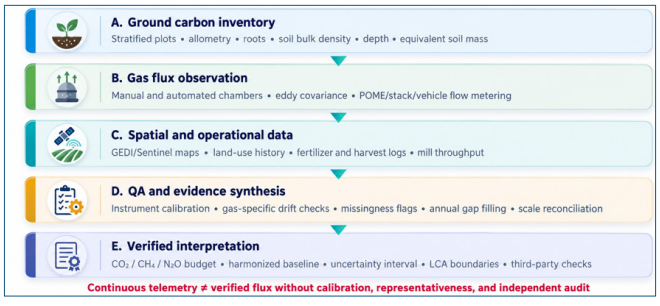


Figure 2: Integrated Monitoring, Reporting and Verification Architecture Separating Field Observations, Independent Quality Checks, Model Reconciliation and Verified Interpretation. An Online data Feed by Itself is not an Independently Audited GHG Balance; the Figure is an Author-Developed Synthesis.

In particular, Figure 2 separates 'measurement obtained' from 'claim validated'. Instruments can stream an unbroken sequence of readings while systematically misrepresenting annual emissions if peak fluxes, calibration drift, missing gases or unobserved land components are excluded. Conversely, a thoughtfully stratified campaign of less frequent measurements may answer a narrow treatment-comparison question convincingly. Robust reporting depends on fitness for a particular purpose: estimating a soil flux requires different evidence from certifying a product footprint or claiming avoided deforestation. The scale-aware integration of ground plots, models and remote sensing can help, but must propagate rather than erase their distinct uncertainties [21,36,44].

Theme V: Mitigation is a Portfolio, not a Single Sequestration Rate

The most consistently defensible mitigation priority is avoiding additional conversion of high-carbon forests and peatlands. Intact forest and peat conservation protects accumulated stocks that would be difficult or impossible to replace through a conventional oil-palm production cycle. Landscape research documents continuing expansion pressures and the direct and indirect consequences of zero-deforestation commitments, which means safeguards must attend to displaced conversion rather than changes confined to one certified supplier. Studies of conservation set-asides and tree islands also show that local conservation and ecological restoration within planted landscapes can produce benefits, though they are not substitutes for protecting intact habitats [4,26,33-35]. On existing mineral-land plantations, management changes can potentially increase retained biomass or soil carbon and reduce emissions intensity. Examples include maintaining protective understory, placing residues strategically, avoiding unnecessary tillage, managing fertiliser timing and improving mill waste treatment. Such measures have to be evaluated for their actual site-level greenhouse-gas consequences and trade-offs with productivity, biodiversity, nutrient cycling and farmer income. Smallholder case studies illustrate that recommended fertiliser and understory practices are constrained by agronomic context; broader LCA evidence indicates that operational improvements can also yield product-footprint reductions. The defensible research question is not whether a practice is universally 'carbon positive', but under which conditions it produces a measurable net improvement [11,32,42,43].

For already-converted peat sites, hydrological management creates substantial but context-specific opportunities. Research on rewetting reports meaningful potential to suppress parts of ongoing peat carbon loss, while the operational implications of water-table adjustment must be assessed across plantation performance, neighboring land, flood dynamics and fire risk. At landscape scale, peat swamp and mangrove conservation and restoration can provide large mitigation opportunities that cannot be replicated solely through improved fertiliser use. A management hierarchy that begins with no further high-carbon land conversion and then pursues reductions on existing estates is thus supported more strongly than one that frames any growing palm plantation as equivalent to a protected forest sink [16,17,55]. The mitigation portfolio must also recognize experimentally observed null results. In established Sumatran oil-palm experiments, increases in understory complexity and riparian restoration treatments produced valuable ecological management opportunities without detectable increases in the measured greenhouse-gas fluxes; this does not demonstrate an immediate quantified net removal. Separately, a large-scale rewetting trial on former plantation peat in Sumatra documented reduced subsidence rates and native

forest regrowth, but subsidence remains a proxy requiring its own assumptions when converted to carbon emissions. Interventions should therefore be described by the outcome actually measured—biodiversity, hydrology, flux reduction or stock gain—rather than labelled generically as sequestration [57,58].

Theme VI: Verification Quality Determines the Credibility of Public Claims

A carbon account may be internally consistent and still fail as a climate claim if it is compared against an inflated baseline. Deforestation counterfactuals are especially sensitive to assumed threat levels, selection of reference regions and future policy conditions. Recent studies of carbon crediting show that credited reductions do not always correspond to comparable atmospheric benefits, while analyses of leakage demonstrate that restrictions in one market can shift production or deforestation elsewhere. Such findings do not render all mitigation projects ineffective, but require cautious, empirically justified and periodically updated crediting baselines [27-29,53]. Governance also influences whether technical claims survive scrutiny. Supplier engagement, traceability of smallholder plots, transparent chain-of-custody data and equitable compliance costs affect the practical reach of deforestation-free rules. Digital infrastructure, including blockchain-style verification concepts, can improve audit trails only when input measurements and stakeholder incentives are reliable. Emerging reviews of oil-palm sustainability governance suggest that engagement can break down when monitoring costs and market benefits are distributed unequally. Consequently, the credibility of a climate-integrity system rests on both scientific instruments and workable accountability arrangements [3,24,25].

Discussion and Analysis: From Measurement to Climate Integrity

Resolving the Apparent Paradox of an Accumulating Plantation that Damages the Climate

The central apparent paradox can be expressed simply: a stand may gain living biomass carbon during one year and still impose a net warming influence when judged against its historical and future landscape consequences. The paradox disappears once three propositions are kept separate. First, growing palms may accumulate carbon within a defined plant compartment; second, the site may simultaneously emit carbon dioxide, methane or nitrous oxide through other pathways; and third, the climate impact of establishing the site depends on the carbon-rich system replaced and the plausible alternative trajectory. Carbon stock, annual gas balance and intervention impact are three distinct estimands rather than three labels for the same quantity. Site-scale field evidence and assessments of conversion-related emissions make this separation essential rather than merely semantic [4,10,12,15]. The distinction also clarifies a second apparent contradiction. Some management practices on existing plantations can be worthwhile even when the original conversion cannot be justified retrospectively. For instance, capturing methane from effluent treatment or improving nutrient management can reduce additional emissions in a production system that is already established. Such reductions should be reported as reductions against appropriate operational baselines, not as cancellation of all previously emitted carbon. Any claim of total climate neutrality would require a broader cradle-to-relevant-endpoint account with justified treatment of historical emissions and residual releases. Current product-based assessments and reviews of mitigation strategies support a portfolio of reduction opportunities but not a blanket designation of oil palm as carbon neutral [9,11,13,51]. Time horizon is equally important. The carbon accumulated in a plantation during one crop cycle can be removed and released after replanting; an area may experience sequential phases of uptake and release. Peat losses may continue across those phases even if living standing biomass temporarily increases, and the accounting implications differ from changes in relatively stable mineral-soil stocks. Long-term projects need repeated measurements and explicit treatment of reversals, not a one-year snapshot extrapolated indefinitely. General assessments of terrestrial carbon storage caution that biophysical potential and permanence are constrained by land management, climatic disturbances and the saturation or instability of certain stores [7,8,17,30]. Evidence extending to 2026 reinforces why these distinctions matter for claims about historical responsibility. The progressive release of old peat carbon following drainage and fire in Central Kalimantan has been observed using radiocarbon methods, supporting the need to disclose irreversible or slow-to-recover losses separately from contemporary palm uptake. Long-term peatland tower records likewise show that the direction of an annual CO_2 exchange can switch under disturbance, so a positive plantation carbon trend in a short study cannot establish durability. These findings strengthen the argument for a historical emissions ledger and multiyear evaluation rather than a claim based exclusively on the age of standing palms [45,46].

A Boundary-Consistent Accounting Ledger and Explicit Claim Types

A transparent accounting system should maintain separate but reconciled ledgers. The ecosystem carbon ledger records initial and final stocks in comparable living, dead and soil compartments, as well as carbon removed through harvest and lost through disturbance. A greenhouse-gas flux ledger records observed or defensibly modelled carbon dioxide, methane and nitrous oxide exchanges by source, with appropriate temporal integration and spatial scaling. An operational and product ledger records emissions associated with fertilisers, energy, transportation, processing, effluent treatment and end uses where these fall within the declared boundary. Finally, a historical land-use ledger allocates conversion-related losses and the corresponding counterfactual scenario to the period and claim for which they are relevant. The resulting architecture accommodates inventories and LCA without double counting the same carbon flow as both a field emission and a downstream process emission [5,11,13,21]. In simplified terms, the change in an included carbon stock can be stated as final stock minus initial stock, whereas a net greenhouse-gas assessment combines the relevant greenhouse-gas sources and removals over a defined period and boundary. No single stock subtraction suffices for all decisions because the emissions expressed as carbon dioxide equivalents also depend on gas-specific characterization choices and on which historical events enter the comparison. Each publication or corporate disclosure should therefore supply a short boundary statement before presenting an aggregate number. Such a statement should name the reference land use, included pools, included gases, climate-equivalence horizon, observation period, harvest treatment, processing boundary and whether any avoided emissions depend on a modelled counterfactual [10,12,28,51].

For reporting, a simplified cumulative greenhouse-gas expression can convert gas-specific mass emissions to CO_2 equivalents only after specifying the assessment horizon and ensuring that every term refers to the same spatial and temporal boundary. Emission masses must be expressed in a consistent mass unit, and stock changes cannot be appended to the sum unless the corresponding

changes are correctly converted to attributable fluxes without double counting. Equation (3) is a bookkeeping convention rather than a causal estimate of the effect of an intervention [10,23,31].

$$E(CO_2e,100) = \Sigma[g \in \{CO_2,CH_4,N_2O\}] E(g) \times GWP_{100}(g) \quad (3)$$

The coefficients in Equation (3) must be documented for the declared 100-year characterisation framework rather than selected ad hoc, and positive or negative emissions must follow the same accounting sign convention. The framework does not confer additionality, permanence or baseline credibility by itself; those dimensions require separate evaluation. For product studies, any allocation of mill co-products and land-use conversion burdens must also be made explicit before comparing results across suppliers [11,54].

Three claim types deserve explicit separation. A 'current stock' claim concerns a specified quantity of retained carbon; a 'management emission reduction' concerns a change in greenhouse-gas output relative to credible current practice; and a 'net removal' claim concerns additional atmospheric carbon withdrawal accompanied by adequate monitoring, baseline justification and durability. Product intensity reduction is a fourth useful category but does not automatically imply a decrease in absolute emissions. Confusion among these categories becomes particularly problematic in carbon markets, where a tonne stated as an avoided emission may be mistaken for an equivalent durable removal. Studies of offsets and deforestation baselines show why this vocabulary is essential for preventing credit overstatement [27-29]. Table 1 crosswalks six common claim types to their minimum supporting evidence and identifies the inference that remains prohibited when that evidence is present. It complements Figure 1 by distinguishing descriptive measurement from causal mitigation, and it provides a reviewer-friendly check on whether each numerical result supports the terminology used in a paper or disclosure. The crosswalk is a conceptual synthesis, not a new dataset [12,46,54].

Table 1: Crosswalk of Carbon-Accounting Claims, Minimum Observations and Inference Limits. The Categories are Proposed for this Qualitative Synthesis and Must Be Adapted to the Declared System Boundary.

Claim / Estimand	Minimum evidence for reporting	Inference not justified by that evidence alone
Standing carbon stock	Matched biomass and soil pools, area, depth, age and calibration	Annual net sink, land-use improvement or additional removal
Carbon stock change	Repeated comparable sampling, interval and uncertainty	Whole-system multigas balance or permanent carbon retention
Net ecosystem CO_2 exchange	Verified footprint, meteorology, gap filling and sign convention	No historic conversion debt, no CH_4/N_2O, or net-zero products
Integrated GHG balance	Source-specific multigas fluxes, consistent units, time and space	Additionality, a credible baseline or durable removal
Mitigation relative to baseline	Explicit counterfactual, leakage tests, reversals and audit trail	Same benefit for every plausible baseline, or equivalence to removal
Product carbon footprint	Functional unit, input inventory, land-use accounting and allocation	Absolute emissions reduction from intensity reduction alone

As Table 1 makes clear, improved measurement does not remove the need for a valid comparison scenario. A verified annual CO_2 flux may support an ecosystem-exchange statement without supporting a carbon-credit award, just as improved product intensity can coexist with growing absolute supply-chain emissions. Reporting multiple estimands in separate but reconciled ledgers is therefore a safeguard against both technical double counting and misleading public communication [27,29].

The Proposed Carbon Integrity Ladder

To organize the evidence, this review proposes a six-rung Carbon Integrity Ladder. The first rung requires matched, fully specified carbon pool inventories; the second demands time-consistent repeated stock observations and age or rotation controls. The third adds defensible carbon and other greenhouse-gas flux closure with adequate observational coverage; the fourth incorporates land-use histories and realistic counterfactuals. The fifth reconciles field and product-system emissions while explicitly propagating uncertainty across methods and years; the sixth adds independent review, additionality, permanence, leakage controls and claim-level safeguards. An assessment that reaches a higher rung is not necessarily a stronger sink; it is a more transparent basis for deciding whether a proposed claim is justified. Figure 3 visualizes this framework as cumulative evidentiary conditions rather than a certification score or scientifically validated index. Its ascending structure reflects the logical dependency of the claims: a method cannot repair a missing baseline merely by collecting faster sensor data, and a rigorous counterfactual cannot compensate for gas measurements that ignore a dominant source. Therefore, each proposed climate statement should disclose the highest relevant rung completed and the unresolved gaps preventing a more comprehensive statement. The ladder is an original interpretive framework advanced by this article for future methodological evaluation.



Figure 3: Proposed Carbon Integrity Ladder Linking Matched Pools, Repeated Inventories, Flux Closure, Land-Use Counterfactuals, Lifecycle Uncertainty and Claim Governance. The Six Cumulative Levels are an Interpretive Framework, not an Empirically Validated Score or Offset-Certification Standard.

One benefit of Figure 3 is that it accommodates enterprises at

different stages of monitoring maturity without encouraging inaccurate claims. A smallholder cooperative might begin with defensible land-use maps, plot inventories and input records, then collaborate with researchers on stratified soil and flux sampling. An estate with advanced sensors might concentrate next on instrument validation, peat stratification, cross-scale checks and historic baseline evidence rather than adding more dashboard indicators. A mill with methane capture equipment might make a substantiated operational emissions reduction claim while acknowledging uncertainty about its supplied fruit's land-use history. The proposed hierarchy makes progress visible without presenting a narrow improvement as comprehensive climate neutrality [2,21,24,25].

A Worked Interpretive Audit of the Central Kalimantan Briefing

The values in the briefing presentation provide a useful demonstration of the ladder's first requirement. For forest plots, the slide labels 191.44 t C ha−1 as biomass carbon; for the three palm classes, it labels totals comprising vegetation and soil carbon, with vegetation components of 6.21, 32.66 and 34.97 t C ha−1 and soil components of 35.63, 41.44 and 51.35 t C ha−1. The plotted 'totals' therefore represent unequal pool boundaries and cannot establish the difference between forest and oil palm total ecosystem stocks. There is no basis in these slides to add a forest soil value, to infer that plantation soils gained a specified amount from their pre-conversion condition, or to calculate a net annual sink from the reported stocks. The source's plot-count note for the forest does not substitute for full sampling details for all strata. Figure 4 reconstructs those reported values as a diagnostic visualisation, deliberately retaining the missing forest-soil compartment rather than filling it with an invented estimate. The figure flags the 0.01 t C ha−1 display inconsistency in the prime-mature category and separates an illustrative data presentation from a pool-equivalent comparison. It is not a recalculation using new field samples, and its bar positions should not be used to rank the four sites by total ecosystem carbon. The diagram turns a source-data weakness into a replicable editorial rule: every comparison must disclose which carbon compartments were measured on every side.

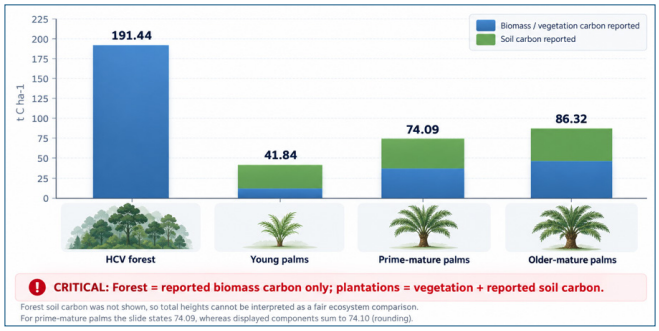


Figure 4: Reconstruction of Preliminary Carbon-Density Values Reported in Kautsar, Slide 7. The Forest Value Includes Biomass Carbon Only, Whereas the Oil-Palm Values Include Both Vegetation and Measured Soil Carbon; Consequently the Visual Heights must not be Interpreted as Comparable Total Ecosystem Stocks. The Prime-Mature Displayed Components add to 74.10 Rather than 74.09 t C ha^{-1}, Consistent with a Small Possible Rounding Discrepancy.

Figure 4 also shows what a follow-up field paper would need to report. Forest and plantation plots should be geographically described and stratified for soil type, drainage, pre-conversion vegetation and stand age; sampling depth, bulk density, coarse fragments, roots and equivalent-soil-mass procedures should be specified. Allometric formulas should be provided with their calibration range, and variance should be estimated using a defensible sampling design that recognises within-estate clustering. Repeated measurements are preferable when the target claim is a sequestration rate, because a cross-sectional sequence of different stands does not automatically estimate a trajectory through time. The supporting soil-carbon methods literature offers practical strategies for more credible change detection and error accounting [19,20,37,40,42]. The field briefing's digital monitoring statements warrant a distinct audit. A claim of data transmission approximately every ten minutes over eight months should prompt an exportable timestamped record with time zones, sensor identifiers, gas species, blank and calibration checks, concentration and flow measurement units, weather or water-table covariates, and flags for failed observations. For field chambers, reviewers should be able to reproduce concentration-to-flux calculations, inspect chamber closure durations and determine the location and representation of each chamber. For stack, transport and effluent sources, data should establish the physical measurement principle and conversion from sampled concentration or operational activity to emissions over the relevant reporting period. Until such evidence is supplied, continuous telemetry is a useful indication of instrument operation but not an independent validation of annual greenhouse-gas emissions [21-23].

Implementation Priorities for Indonesia: Avoid, Reduce, Restore and Verify

An Indonesia-oriented mitigation hierarchy begins with avoidance. Protecting existing high-carbon forests, intact peat and ecologically important set-asides prevents a difficult-to-repay carbon debt and reduces risks to biodiversity and hydrological services. Commitments should cover both direct estate development and displacement across sourcing regions, because supply-chain restrictions can otherwise externalize deforestation. Mapping industrial and smallholder palm distributions, recent forest conversion and potential leakage regions is therefore a foundational governance task, not a peripheral remote-sensing exercise. The empirical literature on oil-palm expansion, zero-deforestation consequences and carbon-rich landscape restoration supports this priority ordering [2,4,17,26,53]. The second priority is reducing controllable emissions on existing land. A practical program may include improving fertiliser targeting and timing, avoiding unnecessary disturbance, retaining beneficial understory, managing harvest residues, maintaining organic ground cover and capturing methane from mill wastewater. Outcomes should be assessed through a matched before-and-after design, comparison plots or credible modelled baselines appropriate to the action, with cost, yield and smallholder implementation constraints recorded. Where reductions affect product intensity, reporting should include both emission intensity and absolute system emissions to reveal possible rebound from output expansion. Agronomic field studies and current palm-oil LCA research provide evidence for these context-sensitive mitigation categories [11,42,43,51].

The third priority concerns ecological recovery and peat risk management. On peat, the central challenge is to slow ongoing oxidation and manage hydrology without exporting flood or drainage impacts to neighboring systems. Research suggests that rewetting may reduce parts of the peat carbon loss, while landscape-level restoration and avoiding further peat conversion can deliver broader climate benefits. On mineral land, tree islands, riparian set-asides and other habitat measures can contribute to diversity

and locally stored biomass, although such ecological co-benefits should be accounted for separately from claimed net removals. A responsible roadmap should monitor water tables, subsidence, fire, biodiversity and local livelihoods alongside greenhouse gases [16,33-35,55]. Verification is the fourth and continuing priority, not a final ceremonial step. Monitoring budgets should be distributed across representative field sampling, laboratory quality assurance, remote-sensing updates, emissions inventories and independent checks. Digital traceability can reduce the burden of collecting records over time, but strong governance also requires transparent protocols, stakeholder participation, appropriate data access and a fair division of compliance costs between large purchasers and smallholder suppliers. The literature on climate crediting and sustainability supply chains underscores that measurement investments generate public value only if those who make claims face meaningful evidence requirements [3,24,27,25].

Research Gaps, Falsifiable Propositions and Future Methods

Several empirical questions emerge from the synthesis. First, do repeated, pool-equivalent inventories show persistent net soil-carbon gains across plantation rotation classes once bulk density, sampling depth and management zones are controlled? Second, what proportion of annual nitrous oxide and methane emissions is missed by sparse chamber schedules in peat and mineral landscapes, and can stratified automatic sampling close that gap? Third, how do the costs and error reductions of combining eddy covariance, chambers, ground inventories and satellite observations vary across industrial estates and smallholder mosaics? These are empirical questions requiring coordinated field studies rather than numerical extrapolation from the source briefing [19,21-23]. A second research program should address climate counterfactuals. Landscape-level studies could compare no-expansion scenarios, intensification on existing mineral-soil plantations, peat rewetting, protection of conservation patches and methane capture at mills using consistent accounting horizons. Their design should capture displacement effects, biodiversity, production and livelihood outcomes, rather than treating a single avoided-tonne estimate as a sufficient decision rule. Zero-deforestation studies and carbon credit integrity research indicate that independent challenge of baseline assumptions is as important as measurement precision in the field [26,28,29,53].

Finally, methods for soil carbon and peat greenhouse-gas assessment should be updated as longer datasets accumulate. Remote imagery and machine learning can direct sampling toward heterogeneous zones, while repeated soil cores and hydrological records can test model drift and quantify detectable trends. Data systems should preserve raw series, environmental context, calibration history, uncertainty propagation, and metadata sufficient to reproduce annual aggregates. Global reviews document gaps in peatland greenhouse-gas observation, strengthening the case for open, long-duration networks across Indonesian production and conservation landscapes. Such programs would permit stronger claims in the future precisely because they are designed to falsify overly optimistic hypotheses [21,40,44,59].

Conclusion and Recommendations

The principal finding is conceptual but has immediate empirical consequences: carbon storage within an oil-palm plantation is not synonymous with annual sequestration, net atmospheric uptake, reduced product emissions or a beneficial land-use transition. These claims measure different quantities and depend on distinct boundaries, reference conditions and time horizons. A growing palm stand may accumulate living carbon at the same time that drainage, land conversion, fertiliser use, wastewater decomposition or processing produces net greenhouse-gas releases. Sound interpretation therefore begins with comparability of carbon compartments and does not permit standing stock measurements to substitute for a complete greenhouse-gas balance. The Central Kalimantan briefing illustrates both the promise of integrated measurement and the danger of overly broad interpretation. Its forest and plantation stock numbers are not total-ecosystem equivalents because the forest value is labelled biomass only, while the palm totals include soil; the material also lacks sufficient technical information to validate the stated continuous monitoring performance. These observations neither discredit the field program nor establish a particular emissions outcome. They identify information that should be disclosed before a field comparison is published as an inferential result or used to substantiate a mitigation claim.

The most defensible mitigation strategy is hierarchical: avoid further conversion of high-carbon forests and peatlands; reduce operational emissions on existing plantations; restore or protect ecological functions where feasible; and independently verify the precise outcome being claimed. Smallholder inclusion, attention to biodiversity and hydrological risk, transparent counterfactuals and displacement safeguards are indispensable components of that strategy. Operational efficiency gains can be real and valuable, but must not be used to obscure historic carbon debt or to reclassify avoided emissions as durable atmospheric removals. The proposed Carbon Integrity Ladder supplies a practical research and reporting agenda. Its cumulative tests require pool-equivalent stocks, adequately sampled multi-gas fluxes, land-use histories, life-cycle reconciliation, quantified uncertainty and claim-level independent safeguards. The priority for follow-up research is not simply collecting more real-time sensor records; it is building longitudinal, stratified and reproducible evidence across soil types, age classes, ownership systems and processing pathways. Under those conditions, oil-palm climate accounting can move from visually persuasive carbon claims toward carefully bounded, auditable and substantively credible conclusions [60].

References

1. Danylo, O., Pirker, J., Lemoine, G., Ceccherini, G., See, L., et al. (2021). A map of the extent and year of detection of oil palm plantations in Indonesia, Malaysia and Thailand. Scientific Data, 8(1), 96.
2. Descales, A., Wech, S., Meija Ard, E., Gateau, D.L., Pendell, S., et al. (2021). High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. Earth System Science Data, 13(3), 1211-1231.
3. Obstfeld, R., Reiner, D.M. (2024). Seeing the forest through the palms: developments in environmentally sustainable palm oil production and zero-deforestation efforts. Frontiers in Sustainable Food Systems, 8, 1398877.
4. Xu, Y., Yu, L., Ciais, P., Li, W., Santoro, M., et al. (2022). Recent expansion of oil palm plantations into carbon-rich forests. Nature Sustainability, 5(7), 574-577.
5. Amelung, W., Bossio, D., de Vries, W., Kögel-Kanner, I., Lehmann, J., et al. (2020). Towards a global-scale soil climate mitigation strategy. Nature Communications, 11(1), 5427.
6. Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargione, J., Sanderman, J., et al. (2020). The role of soil carbon in natural climate solutions. Nature Sustainability, 3(5), 391-398.
7. Nolan, C.J., Field, C.B., Mach, K.J. (2021). Constraints

and enablers for increasing carbon storage in the terrestrial biosphere. Nature Reviews Earth & Environment, 2(6), 436-446.
8. Ruehr, S., Keenan, T.F., Williams, C., Zhou, Y., Lu, X., et al. (2023). Evidence and attribution of the enhanced land carbon sink. Nature Reviews Earth & Environment, 4(8), 518-534.
9. Anaysha, K.E., Zhang, L. (2023). Technology-based comparative life cycle assessment for palm oil industry: the case of Nigeria. Environment, Development and Sustainability, 25(5), 4575-4595.
10. Cooper, H.V., Evers, S., Aplin, P., Crout, N., Dahlan, M.P.B., et al. (2020). Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. Nature Communications, 11(1), 407.
11. De Rosa, M., Schmidt, J., Pasang, H. (2022). Industry-driven mitigation measures can reduce GHG emissions of palm oil. Journal of Cleaner Production, 365, 132565.
12. Meide, A., de La Rua, C., Guillaume, T., Roll, A., Hassler, E., et al. (2020). Measured greenhouse gas budgets challenge emission savings from palm-oil biodiesel. Nature Communications, 11(1), 1089.
13. Wahyono, Y., Hadiyanto, H., Budihardjo, M.A., Adiansyah, J.S. (2020). Assessing the environmental performance of palm oil biodiesel production in Indonesia: A life cycle assessment approach. Energies, 13(12), 3248.
14. Dhandapani, S., Evers, S., Boyd, D., Evans, C.D., Page, S., et al. (2023). Assessment of differences in peat physic-chemical properties, surface subsidence and GHG emissions between the major land-uses of Selangor peatlands. Catena, 230, 107255.
15. McCalmont, J., Kho, L.K., Teh, Y.A., Lewis, K., Chocaholic, M., 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), 2361-2376.
16. McCalmont, J., Kho, L.K., Teh, Y.A., Chocaholic, M., Romping, E., 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.
17. Samiot, S.D., Tillard, P., Adi Nugroho, W.C., Krishnaswami, H., Novita, N., 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(1), 740.
18. Shiraishi, T., Hirata, R., Hayashi, M., Hirano, T. (2023). Carbon dioxide emissions through land use change, fire, and oxidative peat decomposition in Borneo. Scientific Reports, 13(1), 13067.
19. Boivin, P., Lemaitre, T., Clark, J., Guitton Neau, M., Deluz, C. (2025). The single-layer equivalent soil mass method for the evaluation of soil organic carbon stocks: Sources of errors, simplification, and associated detectable change. Ganoderma, 456, 117279.
20. Fowler, A.F., Basso, B., Millar, N., Brinton, W.F. (2023). A simple soil mass correction for a more accurate determination of soil carbon stock changes. Scientific Reports, 13(1), 2242.
21. Guan, K., Jin, Z., Peng, B., Tang, J., DeLucia, E.H., et al. (2023). A scalable framework for quantifying field-level agricultural carbon outcomes. Earth-Science Reviews, 243, 104462.
22. Johannesson, C.F., Nordén, J., Lange, H., Silvennoinen, H., Larsen, K.S. (2024). Optimizing the closure period for improved accuracy of chamber-based greenhouse gas flux estimates. Agricultural and Forest Meteorology, 359, 110289.
23. Stiegler, C., Koebsch, F., Ali, A.A., June, T., Veldkamp, E., et al. (2023). Temporal variation in nitrous oxide (N_2O) fluxes from an oil palm plantation in Indonesia: An ecosystem-scale analysis. GCB Bioenergy, 15(10), 1221-1239.
24. Delambre, I., Lyons-White, J., Melot, C., Egeberg, E.I., Alexander, A., et al. (2023). Should I stay or should I go? Understanding stakeholder dis/engagement for deforestation-free palm oil. Business Strategy and the Environment, 32(8), 5128-5145.
25. El Hat hat, Z., Venkatesh, V.G., Zouadi, T., Sreedharan, V.R., Manimuthu, A., et al. (2023). Analyzing the greenhouse gas emissions in the palm oil supply chain in the VUCA world: A blockchain initiative. Business Strategy and the Environment, 32(8), 5563-5582.
26. Luiten, F., Baldos, U.L.C., Johnson, J.A., Sim, S., Verburg, P.H. (2023). Projecting global oil palm expansion under zero-deforestation commitments: Direct and indirect land use change impacts. science, 26(6), 106971.
27. Probst, B.S., Totzke, M., Monteleone, A., Díaz Anadón, L., Minx, J.C., et al. (2024). Systematic assessment of the achieved emission reductions of carbon crediting projects. Nature Communications, 15(1), 9562.
28. Teo, H.C., Tan, N.H.L., Zheng, Q., Lim, A.J.Y., Sreekar, R., et al. (2023). Uncertainties in deforestation emission baseline methodologies and implications for carbon markets. Nature Communications, 14(1), 8277.
29. West, T.A., Bomfim, B., Haya, B.K. (2024). Methodological issues with deforestation baselines compromise the integrity of carbon offsets from REDD+. Global Environmental Change, 87, 102863.
30. van Noordwijk, M., Aynekulu, E., Hijbeek, R., Milne, E., Minasny, B., et al. (2023). Soils as carbon stores and sinks: Expectations, patterns, processes, and prospects of transitions. Annual Review of Environment and Resources, 48(1), 177-205.
31. Deshmukh, C.S., Susanto, A.P., Nardi, N., Nerolis, N., Kurn Ianto, S., et al. (2023). Net greenhouse gas balance of fire wood plantation on peat in Indonesia. Nature, 616(7958), 740-746.
32. Ahirwal, J., Sahoo, U.K., Thangjam, U., 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, 478-487.
33. Fleiss, S., Waddell, E.H., Ola, B.B., Banin, L.F., Benedick, S., et al. (2020). Conservation set-asides improve carbon storage and support associated plant diversity in certified sustainable oil palm plantations. Biological Conservation, 248, 108631.
34. Montoya-Sánchez, V., Kreft, H., Raimond, I., Baldauf, J., Bertelmann, D., et al. (2023). Landscape heterogeneity and soil biota are central to multi-taxa diversity for oil palm landscape restoration. Communications Earth & Environment, 4(1), 209.
35. Zemp, D.C., Guerrero-Ramirez, N., Brumbach, F., Darras, K., Grass, I., et al. (2023). Tree islands enhance biodiversity and functioning in oil palm landscapes. Nature, 618(7964), 316-321.
36. May, P.B., Schlund, M., Arms ton, J., Kotowska, M.M., Brumbach, F., et al. (2024). Mapping aboveground biomass in Indonesian lowland forests using GEDI and hierarchical models. Remote Sensing of Environment, 313, 114384.

37. Peng, Y., Chahal, I., Hooker, D.C., 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.
38. Sundqvist, M.K., Hasselquist, N.J., Jensen, J., Runesson, J., Goodman, R.C., et al. (2024). Accounting for deep soil carbon in tropical forest conservation payments. Scientific Reports, 14(1), 16772.
39. Rovira, P., Sauras-Yera, T., Romania, J. (2022). Equivalent-mass versus fixed-depth as criteria for quantifying soil carbon sequestration: How relevant is the difference? Catena, 214, 106283.
40. Ruttens, R.J., Reinke, K., Add Insall, M., Bremner, A., Grover, S. (2026). Alternatives to Equivalent Soil Mass in Monitoring, Reporting and Verification of Changes in Soil Carbon. Soil Use and Management, 42(2), e70213.
41. Golicz, K., Cheak, S.C., Jacobs, S., Groe-Stoltenberg, A., Safaei, M., et al. (2024). The older, the better: A comprehensive survey of soil organic carbon under commercial oil palm plantations. Environmental Monitoring and Assessment, 197(1), 86.
42. Rahman, N., Giller, K.E., de Neergaard, A., Magid, J., van de Ven, G., 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.
43. Thomasena, A., Bettauer, R., Juned, H., Baron, V., Cherones, C., 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.
44. Beisekenov, N., Bankia, W., Ajayi, A.D., Hasegawa, H., Tadao, A. (2025). Remote sensing-based soil organic carbon monitoring using advanced machine learning techniques under conservation agriculture systems. Smart Agricultural Technology, 11, 101036.
45. Hirano, T., Ohkubo, S., Itoh, M., Tsuzuki, H., Sakabe, A., et al. (2024). Large variation in carbon dioxide emissions from tropical peat swamp forests due to disturbances. Communications Earth & Environment, 5(1), 221.
46. Karachi, J., Itoh, M., Atarahs-Andoh, M., Saito-Kokubu, Y., Matsueda, M., et al. (2026). Progressive release of long-stored carbon from tropical peatland disturbances. Nature Communications, 17(1), 4369.
47. Aini, F.K., Kerouac's, K., Smith, J.U., Vichot, L., Martius, C. (2020). How does replacing natural forests with rubber and oil palm plantations affect soil respiration and methane fluxes? Ecosphere, 11(11), e03284.
48. Swails, E., Drewer, J., Hartill, J., Comeau, L.P., Vichot, L.V., et al. (2024). Soil nitrous oxide and methane fluxes from a land-use change transition of primary forest to oil palm in an Indonesian peatland. Biogeochemistry, 167(4), 363–381.
49. Kasak, K., Drenova, I., Soosaar, K., Melling, L., Xuan, W.G., et al. (2025). Greenhouse gas emissions from ditches in oil palm plantations on tropical peatlands in Malaysia. Scientific Reports, 15(1), 37126.
50. Middot, F., Goh, K.M., Liew, K.J., Lau, S.Y.L., Essenberg, M., et al. (2025). Temporal dynamics of soil microbial C and N cycles with GHG fluxes in the transition from tropical peatland forest to oil palm plantation. Applied and Environmental Microbiology, 91(1), e01986-24.
51. Fariza, F., Amanda, T., Dachyar, M., Noor, Z.Z., (2024). 2030 oil palm plantation carbon footprint estimation using O-LCA and forecasting. Journal of Cleaner Production, 463, 142646.
52. Basri, M.H.A., McCalmont, J., Kho, L.K., Hartley, I.P., Teh, Y.A., et al. (2024). Reducing bias on soil surface CO_2 flux emission measurements: Case study on a mature oil palm (Elaeis guineensis) plantation on tropical peatland in Southeast Asia. Agricultural and Forest Meteorology, 350, 110002.
53. Yarlagadda, B., Zhao, X., Iyer, G., Wild, T., Hultman, N., et al. (2025). Emissions leakage and economic losses may undermine deforestation-linked oil crop import restrictions. Nature Communications, 16(1), 1520.
54. Brummitt, C.D., Mathers, C.A., Keating, R.A., O'Leary, K., Easter, M., et al. (2024). Solutions and insights for agricultural monitoring, reporting, and verification (MRV) from three consecutive issuances of soil carbon credits. Journal of Environmental Management, 369, 122284.
55. Novita, N., Ashari, A., Riona, R.P., Ganga, A., Ansari, G.Z., et al. (2024). Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands. Science of the Total Environment, 952, 175829.
56. Kerouac's, K., Gonzales, M.L., Málaga, N., 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.
57. Drewer, J., Taigan, R.S., Banin, L.F., White, S., Raine, E., et al. (2024). Restoring understory and riparian areas in oil palm plantations does not increase greenhouse gas fluxes. Frontiers in Forests and Global Change, 7, 1324475.
58. Hoier, A., Verni men, R., Mulyadi, D., Triatoma, V., Hamdani, H., et al. (2024). Benefits of tropical peatland rewetting for subsidence reduction and forest regrowth: Results from a large-scale restoration trial. Scientific Reports, 14(1), 10721.
59. Zhao, J., Weldon, S., Barthelmes, A., Swails, E., Kerouac's, K., et al. (2024). Global observation gaps of peatland greenhouse gas balances: Needs and obstacles. Biogeochemistry, 167(4), 427–442.
60. Kautsar, V. (2026). Climate Change Mitigation in Oil Palm Production: Carbon Storage and Field Measurements. Unpublished 11-slide field and teaching briefing, Faculty of Agriculture, INSTIPER Yogyakarta. Supplied source material.

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