



Oil Palm as a Carbon Sink - or a Conditional Sink? Reconciling Photosynthetic Uptake, Ecosystem Carbon Storage, Land-Use Change, Peat Emissions, and Life-Cycle Greenhouse-Gas Balances

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ABSTRACT

Oil palm is a highly productive perennial crop whose rapid biomass accumulation has encouraged claims that plantations function as major carbon sinks. Yet such claims are scientifically incomplete unless the accounting boundary, previous land cover, soil type, plantation age, harvested carbon, non-CO₂ greenhouse gases, and value-chain emissions are made explicit. This qualitative literature review critically synthesizes peer-reviewed evidence published from 2020 to 2026 on carbon uptake and storage in oil-palm systems, with particular attention to Indonesia and Malaysia. The literature indicates that mature palms can exhibit strong photosynthetic uptake and substantial standing biomass, while young plantations may remain net carbon sources and drained peat plantations can emit large quantities of CO₂ despite vigorous palm growth. Mineral-soil plantations show more heterogeneous outcomes, including possibilities for soil-carbon recovery under improved management, whereas forest-to-oil-palm conversion creates carbon debt that cannot be inferred from plantation biomass alone. Nitrous oxide, methane, palm-oil mill effluent, fertilizer, transport and processing further alter whole-system greenhouse-gas balances. The review therefore proposes a nested accounting framework spanning plant, ecosystem, land-use-transition, value-chain and landscape-governance boundaries

INTRODUCTION

Oil palm (*Elaeis guineensis*) occupies an unusual position in climate and land-use debates. It is a perennial crop with exceptional oil yield per unit area, a long productive life, a large standing biomass relative to annual crops, and strong commercial importance across tropical economies. Those characteristics make it tempting to describe oil-palm plantations as carbon sinks: palms fix atmospheric carbon dioxide through photosynthesis, allocate a share of assimilated carbon to trunks, fronds and roots, and can accumulate substantial biomass over a rotation. Recent syntheses have therefore emphasized the sequestration capacity of oil palm and other tropical crops, while broader assessments acknowledge the crop's economic advantages alongside environmental costs (Murphy, 2024; Qaim et al., 2020). The difficulty is that biological carbon uptake and climate mitigation are not synonymous. Whether a plantation is a net carbon sink depends not only on how much CO₂ the palms absorb, but also on what carbon was lost when the plantation was established, what happens to soil and peat carbon, how much carbon is removed in harvested products, and what greenhouse gases are emitted during cultivation and processing.

This distinction has become especially important because public communication often compresses several very different concepts into one phrase. Gross primary production measures photosynthetic uptake; net primary production subtracts plant respiration; net ecosystem exchange incorporates ecosystem respiration; net ecosystem carbon balance additionally considers lateral transfers such as harvest; land-use-change accounting includes the carbon consequences of replacing the previous ecosystem; and life-cycle assessment extends the boundary further to fertilizer, fuel, milling, palm-oil mill effluent (POME), transport and other processes. Measured greenhouse-gas budgets in Indonesia demonstrate the consequence of ignoring these distinctions: a mature plantation may show negative net ecosystem exchange and thus appear to be a strong on-site CO₂ sink, while the balance changes when harvested carbon and other greenhouse gases are incorporated (Meijide et al., 2020). Similarly, oil palm established on tropical peat can accumulate biomass while the drained peat body remains a large source of CO₂ (Kiew et al., 2020; McCalmont et al., 2021).

Land-use history is equally decisive. A plantation established on existing agricultural land or a low-carbon degraded site does not carry the same carbon debt as one created by clearing carbon-rich tropical forest. Remote-sensing evidence shows that recent oil-palm expansion has continued to replace forests containing substantial biomass carbon, while field studies in Amazonia show that disturbed forests can retain considerably more ecosystem carbon than subsequent oil-palm plantations (Xu et al., 2022; Malaga et al., 2021). Forest conversion also affects soil carbon, and radiocarbon evidence indicates losses and turnover changes after conversion to oil palm in multiple tropical regions (Finstad et al., 2020). Consequently, a plantation's standing biomass cannot be treated as an ecological substitute for the carbon stock of the ecosystem it replaced.

The question is particularly acute on tropical peatlands. Peat is not simply a rooting medium; it is a long-accumulated carbon store whose stability depends strongly on waterlogging. Drainage for plantation agriculture lowers the water table, increases oxygen exposure and accelerates peat decomposition. Direct measurements across conversion stages show that accounting for CO₂, CH₄ and N₂O produces a much larger warming burden than comparing only mature plantation and forest surface fluxes (Cooper et al., 2020). Long-term eddy-covariance evidence further indicates that declining emissions as plantations mature do not necessarily restore a positive whole-system carbon balance because early conversion losses and persistent peat oxidation can dominate the rotation (McCalmont et al., 2021). These results directly challenge any universal statement that an oil-palm plantation is inherently a carbon sink.

The purpose of this qualitative literature review is therefore not to defend or reject oil palm in categorical terms. Instead, it asks under what ecological, temporal and accounting conditions a carbon-sink claim is scientifically defensible. The review integrates contemporary evidence on photosynthetic uptake, above- and below-ground biomass, soil organic carbon, peat oxidation, non-CO₂ greenhouse gases, land-use change, conservation set-asides, agroforestry, rewetting, certification and life-cycle mitigation. It addresses five questions: how should 'carbon sink' be defined for oil-palm systems; how does sink behavior change with plantation age; how do mineral and peat soils differ; how does previous land cover affect the balance; and which management and governance interventions most credibly improve climate performance. The central proposition is that oil palm is best understood as a conditional sink whose status depends on boundary, counterfactual and time horizon rather than on photosynthesis alone.

LITERATURE RIVIEW

A carbon stock is a quantity stored at a point in time, whereas a carbon flux is a rate of transfer. Confusing the two is a common source of overstatement in plantation carbon narratives. A mature oil-palm stand can contain more carbon than a young stand because trunks and roots have accumulated biomass, but that fact says nothing by itself about whether the system is currently removing carbon from the atmosphere or whether its total carbon stock exceeds that of the previous land cover. Lewis et al. (2020) documented rapid above-ground biomass accumulation on tropical peat and developed peat-specific allometries, illustrating why biomass inventories are valuable. Yet the same landscape can simultaneously lose carbon from peat oxidation, so biomass gain must be interpreted alongside soil loss. Murphy (2024) likewise emphasizes substantial photosynthetic sequestration by oil palm, but the climate significance of that uptake depends on the accounting boundary used to evaluate the system. Plant-level accounting begins with gross primary production (GPP), the total carbon fixed through photosynthesis. Plant respiration is then subtracted to estimate net primary production (NPP), which is allocated among new leaves, trunk tissue, roots, reproductive structures and exudates. Ecosystem-level accounting goes further by incorporating heterotrophic respiration from

decomposers and soil organic matter. Eddy-covariance studies typically report net ecosystem exchange (NEE), with negative values conventionally indicating net ecosystem uptake. However, an oil-palm plantation exports a significant share of assimilated carbon in fresh fruit bunches. When harvested carbon is excluded, the ecosystem may appear to sequester more carbon than it actually retains. Meijide et al. (2020) showed precisely this distinction, while Kiew et al. (2020) demonstrated that plantations on peat can remain strong CO₂ sources even when palms are productive.

Land-use-transition accounting adds the counterfactual: what would have happened to carbon stocks if the land had not been converted? This question matters because the climate value of accumulating palm biomass differs sharply between a second rotation on existing plantation land and first-generation conversion of forest or peat swamp. Xu et al. (2022) quantified substantial forest biomass loss associated with oil-palm expansion, and Malaga et al. (2021) found major reductions in ecosystem carbon when disturbed Amazonian forest was converted to oil palm. Quezada et al. (2022) consequently argue that deforestation-free land-use change and organic-matter-centered management can markedly improve the carbon footprint of expansion. The logical implication is that 'additional carbon sequestration' should be assessed relative to a credible baseline rather than inferred from plantation biomass alone.

Life-cycle assessment (LCA) extends the system boundary from field carbon to product climate performance. Fertilizer manufacture and application, field machinery, fuel, transportation, milling, POME treatment and residue management can all affect greenhouse-gas intensity. De Rosa et al. (2022) identify avoidance of peat cultivation, lower drainage intensity, nature conservation and POME biogas capture as major industry-controlled mitigation levers. Organizational LCA for an Indonesian company similarly identified POME, fertilizer and transportation as major projected emission sources (Farizal et al., 2024). More recent comparative work across major producing countries shows that certified and non-certified supply chains can differ substantially in global-warming impact because of differences in peat exposure and methane capture (Schmidt and Weidema, 2026). Thus, a plantation may be a biological CO₂ sink at one boundary while its harvested product still carries a positive life-cycle greenhouse-gas footprint.

These nested boundaries are summarized in Figure 1. The practical value of the framework is that it prevents a valid statement at one scale from being generalized to another. For example, 'the palms accumulate carbon' may be accurate at the plant boundary, but it does not establish that the ecosystem is a net sink, that land conversion was climate-beneficial, or that the delivered tonne of refined oil is carbon-neutral. The broader the claim, the broader the evidence required. This review therefore evaluates carbon-sink claims only when the authors' system boundary, time horizon and counterfactual can be identified.

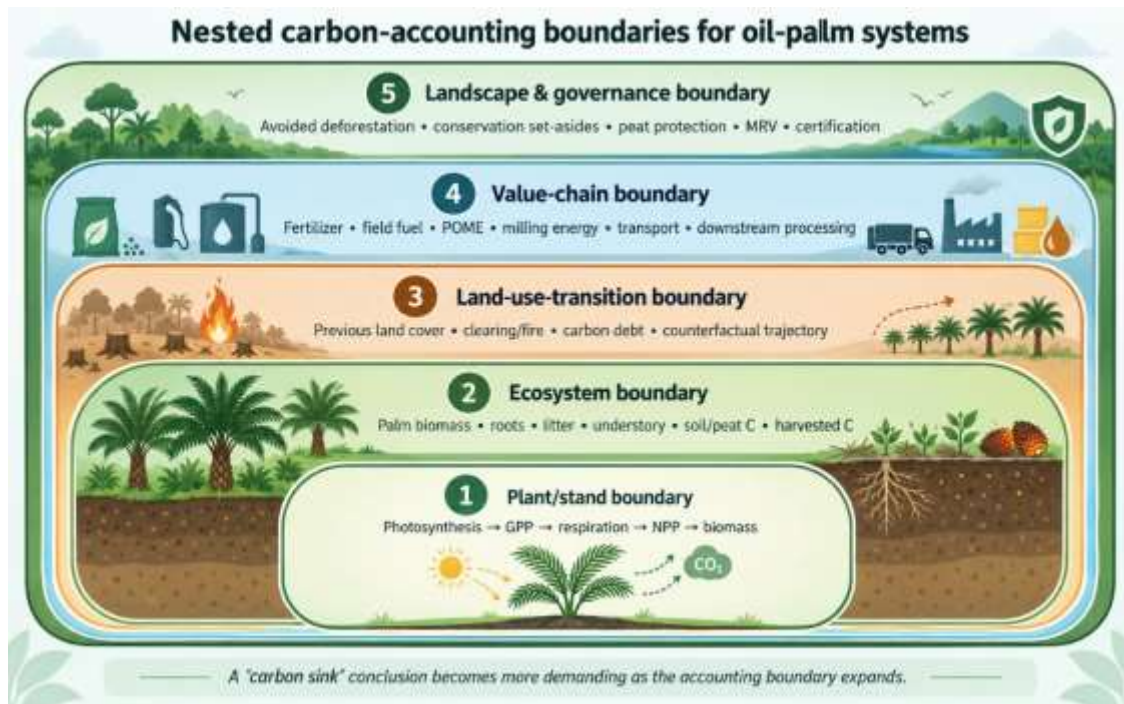


Figure 1. Nested Carbon-Accounting Boundaries for Oil-Palm Systems

Figure 1 should be read from the center outward. At the plant boundary, photosynthesis and biomass accumulation can support a sink claim. At broader boundaries, soil or peat carbon, land-use change, non-CO₂ gases and value-chain emissions are progressively added. A statement that is correct at the inner boundary is therefore not automatically valid at the outer boundary. This nested approach is the organizing framework used throughout the review.

Table 1 translates the nested framework into operational questions for each accounting boundary and makes the principal limitation of each boundary explicit. It clarifies which metrics can support a narrow biological sequestration statement and which additional evidence is required when the claim expands toward land-use, value-chain or landscape-scale climate performance

Table 1. Carbon-Accounting Boundaries and the Questions They Answer

Boundary	Core metrics	Primary question	Main limitation
Plant/stand	GPP, NPP, biomass increment	Does the vegetation accumulate carbon?	Cannot establish whole-system mitigation
Ecosystem	NEE/NEP, soil/peat C, litter, harvest export	Does the plantation ecosystem retain net carbon?	Sensitive to age, soil and harvest accounting
Land-use transition	Previous land cover, conversion loss, carbon debt	Did establishing the plantation improve carbon relative to the counterfactual?	Requires credible baseline and time horizon

Value chain	N ₂ O, CH ₄ , fertilizer, POME, energy, transport	What is the GHG footprint of palm-oil production?	Allocation and technology assumptions matter
Landscape/governance	Avoided deforestation, set-asides, buffers, certification, MRV	Does the production system reduce emissions at landscape scale?	Leakage, enforcement and additionality are decisive

As Table 1 shows, no single metric can validate a carbon-sink claim across all spatial and temporal scales. Cross-study comparisons are therefore meaningful only when accounting boundaries, baselines, time horizons, harvested-carbon treatment and greenhouse gases are made sufficiently comparable.

METHODOLOGY

This study applies a critical qualitative literature review rather than a systematic literature review or meta-analysis. The objective is interpretive synthesis across heterogeneous forms of evidence that cannot be reduced to a single pooled sequestration coefficient. The evidence base includes eddy-covariance measurements, chamber studies, destructive and non-destructive biomass inventories, soil-carbon measurements, peat hydrology studies, remote-sensing analyses, process-based models, life-cycle assessments and governance research. Peer-reviewed journal articles published from 2020 to September 2026 were prioritized, with emphasis on Indonesia and Malaysia because they dominate the contemporary evidence base on oil-palm carbon dynamics. Comparative evidence from Amazonia, Africa and India was included where it clarified the role of previous land use, farming intensity or agroforestry.

Literature identification used combinations of the terms oil palm, *Elaeis guineensis*, carbon sink, carbon sequestration, biomass carbon, net ecosystem exchange, soil organic carbon, peat, greenhouse gas, nitrous oxide, methane, land-use change, carbon debt, life-cycle assessment, certification, rewetting, riparian buffer, agroforestry and POME. Searches were conceptually organized rather than PRISMA-based because the purpose was to build a thematic and explanatory synthesis, not to estimate an exhaustive effect size. Priority was given to studies with transparent methods, peer-reviewed publication status and direct relevance to one or more of the review's five accounting layers.

Evidence was coded into five analytical layers: (1) plant and stand carbon uptake, including photosynthesis and biomass accumulation; (2) ecosystem carbon, including above- and below-ground biomass, litter, understory and soil or peat; (3) land-use-transition effects, including previous vegetation, conversion emissions and carbon debt; (4) value-chain greenhouse gases, including fertilizer, field energy, POME, milling and transport; and (5) landscape governance, including conservation set-asides, riparian buffers, certification, traceability and restoration. Additional codes captured plantation age, soil type, water-table

depth, management intensity, measurement method and whether harvested carbon was included.

A key interpretive rule was to preserve contradictory evidence rather than average it away. For example, positive biomass accumulation on peat and large peat carbon emissions are not inconsistent measurements; they describe different pools in the same system. Similarly, mature stands showing net atmospheric uptake at the plantation boundary can coexist with large historical carbon debt from forest conversion. Methodological differences were treated as substantive because sampling frequency, chamber placement, allometric equations and model assumptions can materially change estimates. Basri et al. (2024) showed that time-of-day sampling can bias chamber-based peat CO₂ estimates, while Swails et al. (2022) demonstrated that process-based emission factors vary through the plantation rotation. Such evidence justifies a qualitative framework that emphasizes boundary sensitivity and uncertainty.

The resulting synthesis classifies evidence as strong, moderate, context-dependent, or insufficient. Strong evidence refers to patterns replicated across methods or locations, such as the high emissions risk from drained peat and the importance of avoiding new forest conversion. Context-dependent evidence includes the capacity of mineral-soil plantations to rebuild soil carbon under particular management regimes or the magnitude of climate benefits from agroforestry. Promotional and other non-peer-reviewed materials were used only to identify recurrent public claims and were not treated as scientific evidence. The review instead tests whether such claims remain valid when broader ecosystem, land-use, greenhouse-gas and life-cycle accounting boundaries are applied.

RESULT

Photosynthetic uptake is real, but it is not equivalent to a whole-system sink.

Oil palm is a fast-growing perennial that can accumulate substantial above-ground biomass during establishment and maturation. Destructive and non-destructive measurements on tropical peat found strong biomass accumulation during the first twelve years after planting, confirming the crop's capacity to transfer atmospheric carbon into standing plant material (Lewis et al., 2020). Mature canopies can therefore support high carbon uptake, and the crop's perennial structure gives it a larger standing biomass pool than annual oilseed crops. However, the correct inference is limited: photosynthetic uptake establishes a gross biological flux, not a net climate balance. Ecosystem respiration, soil decomposition, harvested fruit, pruning, mortality and downstream emissions determine how much of the assimilated carbon is actually retained.

Measurement-based carbon budgets illustrate the age dependence of this process. Meijide et al. (2020) reported that a young Indonesian plantation was a substantial carbon source while a mature plantation exhibited strong net CO₂ uptake based on NEE. This shift reflects increasing canopy development and biomass accumulation, but it also exposes the danger of using a single fixed annual sequestration coefficient for the entire plantation cycle. Figure 2

summarizes the conceptual trajectory: standing biomass rises through the immature and mature phases, while soil carbon may follow a very different path. Replanting eventually removes or redistributes a large portion of standing biomass and restarts the cycle. The net balance therefore depends on the integration period and whether exported or decomposed biomass is counted.

The plantation-age effect is also evident below ground. A large Malaysian survey found lower soil organic carbon in immature and young mature replanted fields than in older mature plantations, suggesting that SOC can recover as plantations age under some commercial conditions (Golicz et al., 2025). Yet this pattern should not be interpreted as proof that conversion to oil palm increases soil carbon relative to forest. Radiocarbon analysis across tropical regions documented carbon-stock losses after land-use change to oil palm, while management studies in Sumatra show that residue handling and other practices can influence SOC within existing plantations (Finstad et al., 2020; Rahman et al., 2021). Hennings et al. (2022) further found that management extensification can reduce SOC decomposition, supporting the view that management can improve the trajectory of an already-established plantation without erasing the carbon cost of earlier conversion. Long-term field evidence from Lampung further shows that repeated empty-fruit-bunch recycling can increase soil organic carbon under specific application regimes, although the magnitude is spatially heterogeneous and not maximized simply by applying the highest residue rate (Noirot et al., 2022).

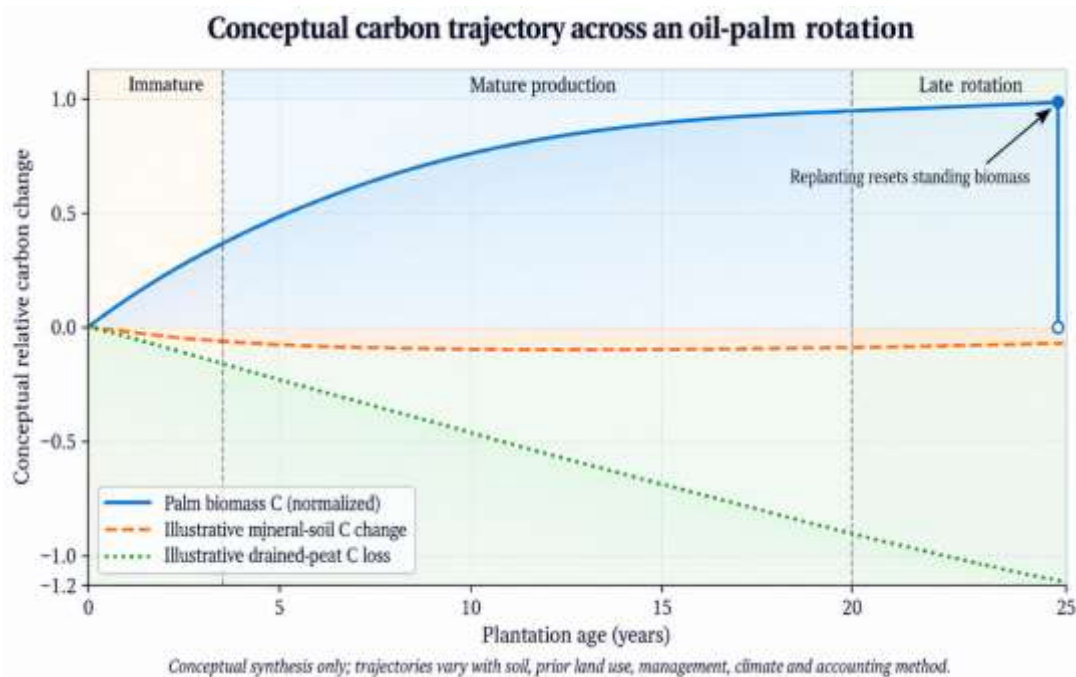


Figure 2. Conceptual Carbon Trajectory Across an Oil-Palm Rotation

Figure 2 illustrates that standing palm biomass normally increases as the plantation matures, but soil-carbon trajectories differ by soil type and management. The dashed mineral-soil line illustrates that initial losses can be followed by partial recovery, whereas the dotted peat line illustrates persistent

carbon loss under drainage. The curves are conceptual rather than empirical averages; their purpose is to show why plantation age and soil type must be integrated before assigning a sink or source label.

2. Mineral Soils and Peat Soils Generate Fundamentally Different Carbon Narratives

On mineral soils, the major climate concerns are the loss of forest biomass during conversion, changes in soil carbon, fertilizer-related N₂O and the balance between biomass accumulation and harvested output. Drewer et al. (2021) found higher nitrous-oxide emissions from oil-palm plantations than from adjacent logged forest on mineral soil, showing that non-CO₂ gases can offset part of the apparent benefit from biomass carbon. Rahman et al. (2021) nevertheless demonstrate that plantation management can influence SOC stocks, creating a legitimate mitigation opportunity through residue retention and improved soil stewardship. These findings support a conditional view: mineral-soil plantations established on low-carbon land and managed well can have substantially better climate performance than those created through forest conversion.

On peat, the problem is more structural because drainage exposes a pre-existing carbon reservoir to aerobic decomposition. Kiew et al. (2020) measured a plantation-level CO₂ balance on tropical peat and found the system to be a large source. Cooper et al. (2020) showed that conversion from peat swamp forest to oil palm generates large combined CO₂, CH₄ and N₂O emissions across conversion stages, while McCalmont et al. (2021) found that emissions decline as palms mature but the system remains a substantial net carbon source over the observed period. Dhandapani and Evers (2020) add another risk pathway: fire associated with peatland management can sharply increase greenhouse-gas emissions and reduce peat carbon. Broader peatland syntheses and comparative studies likewise show that drainage status, vegetation recovery and conservation condition strongly shape the greenhouse-gas balance (Ribeiro et al., 2021; Azizan et al., 2021; Deshmukh et al., 2021). Together, these studies make drained peat one of the clearest cases where palm biomass accumulation cannot justify a generic carbon-sink label. Surface fluxes are also spatially heterogeneous within peat plantations, with dry-season differences among management zones reinforcing the need for spatially representative sampling rather than reliance on a single chamber location (Dhandapani, 2022).

Hydrology is the critical control variable in peat systems. Process-based modeling indicates that peat CO₂ and N₂O emission factors vary over the rotation and respond to precipitation, water-table depth, soil C:N ratio and mineral nitrogen (Swails et al., 2022). Field studies suggest that shallower water tables may reduce peat carbon loss without necessarily imposing the severe productivity penalty often assumed in plantation management (McCalmont et al., 2023). Rewetting evidence from West Kalimantan is especially relevant: Novita et al. (2024) observed significant reductions in peat CO₂ emissions after rewetting, although rewetted plantations did not return to the low-emission state of secondary forest. This supports rewetting as mitigation for existing degraded peat plantations while reinforcing the superior climate logic of avoiding peat conversion in the first place.

Peat accounting must also include non-soil microenvironments. Drainage ditches can become methane-emitting zones even when drained peat surfaces show reduced CH₄ fluxes. Kasak et al. (2025) documented measurable CO₂ and CH₄ emissions from plantation ditches in Malaysia, emphasizing that hydrological infrastructure itself belongs inside the system boundary. Nishina et al. (2023) similarly found dissolved N₂O in plantation drainage on peat, adding an indirect pathway that can be missed by surface-chamber measurements. Chaddy et al. (2026) further showed that long-term nitrogen fertilization can alter methane dynamics in drained tropical peatland. These studies demonstrate why full greenhouse-gas budgets require spatially explicit sampling of palms, interrows, frond piles, drainage features and water pathways rather than a single 'representative' chamber location.

3. Non-CO₂ Greenhouse Gases Materially Alter the Balance

Nitrous oxide has a high global-warming potential and is closely linked to nitrogen cycling and fertilizer management. Skiba et al. (2020) highlighted major gaps in N₂O data for oil palm and cautioned against treating CO₂ as the only relevant greenhouse gas. Swails et al. (2021) showed substantial spatial and temporal variability in peat CH₄ and N₂O fluxes, and Swails et al. (2024) traced greenhouse-gas changes along a forest-to-oil-palm transition in Indonesian peatland. The implication is methodological as much as agronomic: a carbon accounting exercise based only on tree biomass or CO₂ flux can misclassify systems whose N₂O or CH₄ emissions are substantial.

Measurement uncertainty also influences reported sink strength. Manual chamber measurements are often concentrated during daytime working hours, yet soil respiration varies diurnally. Basri et al. (2024) demonstrated that sampling time can bias plantation-scale peat CO₂ estimates and recommended automatic or bias-corrected approaches. Chamber studies also vary in whether they sample palm bases, harvesting paths, frond piles and drains. Eddy covariance integrates larger spatial areas but requires careful treatment of flux footprints, data gaps and harvested-carbon exports. Allometric approaches are efficient for biomass monitoring but depend on equations developed for appropriate soil types and plantation forms. The strong performance of peat-specific allometries reported by Lewis et al. (2020) illustrates the benefit of context-specific calibration. Remote-sensing and LiDAR approaches can complement plot measurements by characterizing vegetation structure over larger and more heterogeneous plantation areas; recent work in Sumatran oil-palm agroforests shows that airborne and terrestrial LiDAR capture complementary three-dimensional structural information useful for monitoring restoration trajectories (Montoya-Sanchez et al., 2024).

4. Land-Use History Determines Whether Biomass Accumulation Represents Climate Recovery or Continuing Carbon Debt

Remote-sensing evidence demonstrates that oil-palm expansion into forest has caused large biomass-carbon losses in Indonesia and Malaysia (Xu et al., 2022). Gaveau et al. (2022) found that deforestation trends in Indonesia have slowed alongside reduced oil-palm expansion and changing economic conditions, suggesting that policy and market context can materially change the land-use component of palm-oil emissions. In Amazonia, Malaga et al. (2021)

showed that disturbed forest still contained substantially more ecosystem carbon than oil-palm plantations across the modeled rotation. The common lesson is that even degraded forest can be a high-carbon baseline relative to plantation, so 'degraded' should not be assumed to mean 'low carbon.'

The carbon-debt concept therefore needs to be explicit in any sink claim. A plantation on previously cleared agricultural land may accumulate new perennial biomass without causing a large new vegetation-carbon loss. By contrast, conversion of intact or logged forest creates an immediate emissions pulse and foregoes future forest carbon storage. Quezada et al. (2022) show that deforestation-free land-use change combined with organic-matter-centered management can improve the carbon footprint of oil-palm expansion. Ariesca et al. (2023) likewise discuss land-swap strategies intended to redirect production toward areas with lower environmental cost. These approaches do not make oil palm intrinsically carbon-negative; rather, they reduce the initial carbon debt against which subsequent sequestration must be evaluated.

5. Management Can Improve Carbon Retention Inside Existing Plantation Landscapes

Conservation set-asides are one of the clearest examples. Fleiss et al. (2020) found that forest set-asides within certified plantations stored substantially more above-ground carbon than oil palm and simultaneously supported plant diversity. Riparian buffers provide additional landscape functions: Williamson et al. (2021) showed that sufficiently wide buffers create cooler, more humid microclimates, while Deere et al. (2022) reported biodiversity benefits and Pashkevich et al. (2022) found that buffers consisting mainly of mature palms have inconsistent ecological effects. The key distinction is that retaining or restoring structurally complex forest vegetation is more likely to deliver carbon and biodiversity co-benefits than simply designating a narrow strip of plantation as a buffer.

Agroforestry and understory management offer another route for increasing ecosystem carbon without clearing new land. Ahirwal et al. (2022) reported higher ecosystem carbon stock in an oil-palm agroforestry treatment in northeast India, demonstrating the potential of diversified systems on degraded land. Drewer et al. (2024) found that restoring understory and riparian areas in oil-palm plantations did not increase greenhouse-gas fluxes, addressing a practical concern that ecological restoration within plantations might create an emissions penalty. However, such interventions should be framed as improvements to existing production landscapes rather than substitutes for conserving natural forests, whose structural complexity and long-term carbon stocks remain much greater. Evidence from the eastern Amazon likewise indicates that oil-palm agroforestry can improve surface-soil chemical and biological health and maintain favorable carbon indicators under conservation-oriented management (Gomes et al., 2024). Long-term enrichment experiments in Sumatra further show that combining planted native trees with natural regeneration increases vegetation structural complexity, strengthening the case for diversified restoration within existing plantation landscapes (Kikuchi et al., 2024).

Nutrient management involves a different trade-off. Low-input smallholder systems can reduce dependence on synthetic fertilizer but may experience nutrient depletion and yield loss. Essono et al. (2023) found that limited inputs in Cameroon constrained nutrient availability even where SOC losses were relatively modest. Lower yield can indirectly increase land demand if total production targets are fixed, whereas excessive nitrogen can increase N₂O emissions. The mitigation problem is therefore not simply 'use less fertilizer' but optimize nutrient-use efficiency, match application to crop demand, recycle organic residues and avoid practices that shift environmental burdens elsewhere. Jaroenkietkajorn and Gheewala (2021) similarly emphasize the need to evaluate GHG, water, land and biodiversity as an integrated nexus rather than as isolated indicators.

6. Value-Chain Emissions Can Dominate After the Plantation Gate

POME is a particularly important source because anaerobic decomposition produces methane. De Rosa et al. (2022) identify biogas capture as one of the most effective industry-driven mitigation measures, alongside avoiding peat and reducing drainage depth. Farizal et al. (2024) project that POME, fertilizer and transportation remain major organizational carbon-footprint sources in an Indonesian case study. Jamaludin et al. (2024) therefore propose an integrated mitigation model for net-zero palm-oil operations, while Rajakal et al. (2024) review technology gaps and opportunities across estates and mills, including biomass utilization, methane management and energy-system changes. These studies shift the discussion from 'how much carbon do palms store?' to 'how much climate forcing is associated with a tonne of palm-oil product?' Beyond capture alone, process-optimization studies show that POME can be converted into biomethane through integrated anaerobic treatment pathways, creating a technically credible route for reducing uncontrolled methane release while recovering energy (Ng et al., 2023).

Certification and governance influence these outcomes but do not eliminate them automatically. Santika et al. (2021) show that certification can have social and village-level implications, while Watts et al. (2021) document barriers faced by Indonesian smallholders seeking certification. Choiruzzad et al. (2021) identify governance ambiguities in Indonesia's sustainability certification regime, and Abdul Majid et al. (2021) review differences among major certification frameworks. The climate relevance is that standards can reduce exposure to peat conversion, promote high-conservation-value set-asides, require GHG accounting and encourage methane capture, but implementation quality and smallholder inclusion matter. The latest comparative LCA evidence indicates lower global-warming impacts for certified palm oil on average, driven substantially by reduced peat cultivation and more POME biogas capture rather than by certification as a label in itself (Schmidt and Weidema, 2026). Earlier comparative life-cycle evidence also found substantially lower greenhouse-gas impacts for certified than non-certified palm oil, with differences linked to peat exposure, yield and the prevalence of POME biogas capture (Schmidt and De Rosa, 2020).

The social dimension matters because climate strategies that cannot be adopted by smallholders may have limited landscape impact. Fosch et al. (2023) argue that replanting unproductive smallholder plantations can support sustainability objectives by increasing output without proportional area expansion. Better yields can reduce pressure for new land, but only if governance prevents rebound expansion and ensures that replanting does not displace remaining forests. Jaroenkietkajorn et al. (2021) show that land use for oil palm produces interacting biodiversity and ecosystem-service costs, reinforcing the need to assess carbon mitigation within a broader sustainability framework. Carbon policy that optimizes a single metric while ignoring land tenure, livelihoods or biodiversity can create perverse incentives and weak long-term compliance.

DISCUSSION

The literature supports a precise answer to the article's central question: oil palm can function as a carbon sink at particular biological and ecosystem boundaries, but 'oil palm plantation' is not synonymous with 'net carbon sink.' The strongest evidence for sink behavior occurs when mature palms are evaluated over a limited plantation boundary and when biomass accumulation and net atmospheric CO₂ uptake exceed contemporaneous ecosystem losses. Meijide et al. (2020) provide a clear empirical example of mature-stand uptake, while Lewis et al. (2020) and Murphy (2024) demonstrate the magnitude and biological basis of biomass accumulation. Yet peat studies show that positive plant sequestration can coexist with net ecosystem emissions, and land-use studies show that plantation carbon can coexist with unresolved carbon debt from forest conversion (Cooper et al., 2020; McCalmont et al., 2021; Xu et al., 2022). The concept is therefore conditional, scale-dependent and time-dependent. This conclusion resolves an apparent contradiction in public debate. One side emphasizes that oil palm is photosynthetically efficient and stores carbon in biomass; the other emphasizes deforestation, peat oxidation and life-cycle emissions. Both can be empirically correct because they refer to different components of the carbon system. The scientific problem arises only when evidence from a narrow component is used to make a broad claim. A palm can be a carbon sink while the plantation is a carbon source; a plantation can be a temporary ecosystem sink while the land-use transition remains a net source; and a field system can sequester carbon while the supply chain still has a positive greenhouse-gas footprint. Figure 3 turns these distinctions into a decision logic for evaluating future claims.



Figure 3. Decision Framework for Evaluating an Oil-Palm Carbon-Sink Claim

Figure 3 illustrates that the decision tree converts the review findings into a claim-validation sequence. A carbon-sink label is defensible only after specifying the boundary, testing the land-use counterfactual, checking whether biomass gains exceed ecosystem losses, and incorporating non-CO₂ and value-chain emissions when the claim is about climate performance. If these conditions are not met, the scientifically appropriate classification is net source, unresolved balance, or a narrower plant-level sequestration statement.

The first decision is the accounting boundary. A plant-level statement should be written as a plant-level statement: for example, mature oil palms accumulate substantial biomass carbon. If the claim is ecosystem-level, then soil, roots, litter, understory, heterotrophic respiration, and harvested carbon must be included. If the claim is about climate mitigation from land conversion, previous land cover and the counterfactual trajectory must be included. If the claim concerns the carbon footprint of palm oil, fertilizer, N₂O, CH₄, POME, milling, transport and co-product allocation must be included. The practice of presenting a single number for 'CO₂ absorbed per hectare per year' without these qualifiers is therefore unsuitable for academic or policy use because it obscures what the number represents and what it excludes.

The second decision is land-use history. Carbon accounting should assign the highest priority to avoiding new carbon debt rather than maximizing sequestration after high-carbon conversion. The literature strongly supports deforestation-free expansion and peat protection as first-order climate strategies (Quezada et al., 2022; De Rosa et al., 2022). This ordering is important because the time required for plantation biomass to compensate for forest or peat losses

can be very long or effectively unattainable within a normal rotation. Conservation set-asides and buffers can retain carbon and biodiversity within production landscapes, but they cannot fully compensate for clearing high-carbon ecosystems elsewhere (Fleiss et al., 2020; Williamson et al., 2021). A credible 'carbon sink' narrative must therefore begin with the baseline land condition, not with the photosynthetic rate of the replacement crop.

The third decision is soil type and hydrology. On mineral soils, improved management can plausibly increase or protect SOC and reduce non-CO₂ emissions, especially in second-generation plantations where the major historical land-use change has already occurred. On peat, drainage-induced oxidation fundamentally changes the balance. Rewetting and shallower drainage can substantially reduce emissions, but the evidence does not support treating rewetted plantation as equivalent to intact peat-swamp forest (Novita et al., 2024; McCalmont et al., 2023). Peat mitigation should therefore be framed as damage reduction and restoration of hydrological function rather than proof that drained peat plantations are net sinks.

The fourth decision is the greenhouse-gas portfolio. N₂O and CH₄ are not secondary technical details; they can materially alter global-warming impact. Oil-palm climate accounting should move from 'carbon accounting' in the narrow sense toward 'greenhouse-gas accounting' whenever the policy question is climate mitigation. Skiba et al. (2020) and Drewer et al. (2021) show the relevance of N₂O, while Nishina et al. (2023) and Kasak et al. (2025) demonstrate that drainage systems can transport or emit gases that plot-based carbon inventories miss. This is especially important for certification and carbon-market claims, where methodological incompleteness can translate directly into over-crediting. The fifth decision is permanence. Oil-palm biomass is not a permanent geological store; it is a managed biological stock that cycles through harvesting, pruning, mortality and replanting. At the end of a rotation, trunks and other residues may decompose, be burned, be converted into products, or be used for energy. The climate value of standing biomass therefore depends partly on what happens after felling. Recent work on biomass utilization and mill decarbonization shows opportunities to substitute fossil energy or create useful products, but benefits depend on counterfactual energy systems, processing emissions and product lifetimes (Rajakal et al., 2024; Jamaludin et al., 2024). A carbon sink claim should consequently specify both the accumulation phase and the fate of biomass at replanting.



Figure 4. Mitigation Hierarchy for Lower-Carbon Palm-Oil Production

Figure 4 illustrates that the hierarchy prioritizes avoided carbon debt over compensatory sequestration. Preventing new forest and peat conversion generally avoids larger and more immediate emissions than attempting to recapture the same carbon after conversion. The subsequent tiers retain carbon in existing landscapes, manage soil and water, decarbonize mills, and strengthen MRV. The sequence is intended as a governance priority, not as a claim that lower tiers are unimportant.

A mitigation hierarchy follows from these findings (Figure 4). The highest priority is to avoid conversion of intact forest, high-carbon secondary forest and peat. The second is to retain carbon already present in plantation landscapes through conservation set-asides, riparian vegetation, understory recovery and residue management. The third is to manage soils and water more effectively, including nutrient optimization, reduced disturbance, fire prevention and rewetting where peat plantations are degraded or being phased out. The fourth is to decarbonize mills through methane capture, energy efficiency and residue valorization. The fifth is to strengthen measurement, reporting and verification so that claims state their boundaries, baselines and uncertainties. This hierarchy is consistent with the evidence that the largest avoidable emissions often come from land-use change and peat, whereas sequestration gains inside existing plantations are important but smaller in system-wide terms (De Rosa et al., 2022; Farizal et al., 2024; Schmidt and Weidema, 2026).

For Indonesia, this framework has direct implications for national climate strategy. Replanting and yield improvement on existing plantations can help meet production objectives while reducing pressure for expansion, especially if accompanied by safeguards against rebound effects (Fosch et al., 2023). Peat rewetting can provide meaningful mitigation in degraded plantations and should be integrated with fire prevention and alternative livelihood planning (Novita et al., 2024). Landscape conservation areas can preserve additional carbon stocks and biodiversity within certified concessions (Fleiss et al., 2020). At the mill level, POME methane capture is technically mature and should be treated as a mainstream emissions-control measure rather than an optional sustainability add-on (De Rosa et al., 2022; Rajakal et al., 2024).

Carbon markets require even stricter discipline. A project that credits oil-palm biomass accumulation must demonstrate additionality: would the carbon have been stored without the project? It must also address leakage, permanence, land-use baseline, soil carbon and non-CO₂ emissions. Crediting a plantation created by clearing forest would be conceptually perverse if only the subsequent palm growth were counted. Similarly, crediting routine biomass growth in an established plantation would require evidence that the credited management intervention increases sequestration beyond business as usual. The five-layer framework proposed here can serve as a screening tool for such claims, although project-level methodologies would require more explicit quantification and verification protocols.

The review also identifies a communication problem. Infographics and corporate sustainability materials often compare annual CO₂ uptake by plantation vegetation with static forest carbon stocks or omit the forest's own annual sequestration and avoided-emission value. Such comparisons mix stocks and flows and may compare different spatial or temporal boundaries. Academically defensible communication should instead disclose whether a number represents gross uptake, net ecosystem exchange, net ecosystem carbon balance, change in ecosystem carbon stock, avoided emissions or product life-cycle intensity. It should also state plantation age, soil type, previous land cover, measurement period and gases included. The objective is not to diminish genuine sequestration by oil palm but to prevent a valid component from being presented as the whole climate balance.

Important evidence gaps remain. Full-rotation studies that follow the same plantations from establishment through replanting are still rare, particularly on mineral soils. Smallholder systems are underrepresented in intensive greenhouse-gas measurement campaigns, even though management, fertilizer access and yield gaps differ from industrial estates (Watts et al., 2021; Essono et al., 2023). Deep-soil carbon and root dynamics are less well constrained than above-ground biomass, and peat emission estimates remain sensitive to hydrology, microtopography and sampling method. Process-based models are improving temporal representation (Swails et al., 2022), but model calibration remains limited by field data. Research should therefore prioritize harmonized protocols that combine eddy covariance, chamber measurements, biomass inventories, soil profiles, remote sensing and explicit harvested-carbon

accounting. Combining field flux measurements with scalable structural monitoring is particularly promising because LiDAR can resolve canopy and vegetation-complexity attributes that are difficult to capture consistently through ground inventories alone (Montoya-Sanchez et al., 2024).

Governance research likewise needs to connect carbon metrics to institutional performance. Certification can establish requirements, but implementation depends on audit quality, traceability, land-tenure clarity, incentives and the ability of smallholders to comply. The governance ambiguities identified by Choiruzzad et al. (2021) and the certification barriers described by Watts et al. (2021) show why technical carbon standards alone are insufficient. Socially inclusive decarbonization requires finance for replanting, extension support, accessible methane-capture investments for mills, and credible monitoring systems that do not exclude independent smallholders. Santika et al. (2021) further remind us that certification affects livelihoods and village well-being as well as environmental metrics, so climate interventions should be evaluated within broader sustainable-development outcomes.

Finally, the review suggests a more constructive framing for the palm-oil debate. The relevant comparison is not 'oil palm versus no oil palm' but among alternative ways of meeting demand for vegetable oil, livelihoods and industrial feedstocks under land and climate constraints. Oil palm's high land productivity is a real advantage, but it becomes a climate advantage only when expansion avoids high-carbon ecosystems and when existing supply chains reduce operational emissions. Jaroenkietkajorn et al. (2021) and Jaroenkietkajorn and Gheewala (2021) show why land, biodiversity, water and greenhouse gases must be assessed jointly. The strongest climate case for oil palm therefore lies in producing more efficiently on suitable existing land, protecting forests and peat, improving soil and landscape management, and decarbonizing mills - not in asserting that any hectare planted with palms is automatically a carbon sink.

CONCLUSIONS AND RECOMMENDATIONS

Oil palm is unquestionably capable of rapid photosynthetic carbon uptake and substantial biomass accumulation, especially as plantations mature. Those biological facts justify describing palms, and in some circumstances mature plantation stands, as active carbon sinks over specified periods. They do not justify a universal claim that oil-palm plantations are net carbon sinks. Whole-system outcomes depend on plantation age, previous land cover, soil type, peat hydrology, harvested-carbon export, management, non-CO₂ greenhouse gases and the boundary used for accounting. Evidence from drained tropical peat is particularly strong: palm growth can coexist with large net ecosystem emissions. Evidence from mineral soils is more heterogeneous and offers greater scope for improved management, especially where plantations are established on existing agricultural land rather than by clearing forest.

The most defensible policy approach is therefore hierarchical. First, avoid new conversion of intact forest, carbon-rich secondary forest and peat. Second, improve the carbon performance of existing plantations through soil stewardship, residue retention, diversified understory, conservation set-asides,

riparian protection and precision nutrient management. Third, reduce peat emissions through higher water tables and rewetting where ecologically and socially feasible. Fourth, capture methane from POME, improve mill energy efficiency and use residues in ways that produce verifiable fossil-energy substitution or durable carbon benefits. Fifth, strengthen MRV so that carbon claims disclose boundary, counterfactual, time horizon, gases, uncertainty and treatment of harvested biomass.

For research, priorities include full-rotation carbon budgets, harmonized mineral-soil and peat measurement protocols, deeper soil and root observations, more representative smallholder studies, integration of remote sensing with field fluxes, and explicit links between plantation carbon models and product-level LCA. For governance, certification and carbon-market methodologies should reject stock-flow comparisons that count palm growth while excluding carbon debt or non-CO₂ emissions. The scientifically appropriate conclusion is therefore neither that oil palm is climate-neutral nor that its sequestration is irrelevant. Oil palm is a conditional carbon sink whose climate value emerges only when biological uptake is evaluated within the complete ecological and supply-chain context.

FURTHER STUDY

This research still has some limitations, so further studies are needed on the topic Oil Palm as a Carbon Sink - or a Conditional Sink? Reconciling Photosynthetic Uptake, Ecosystem Carbon Storage, Land-Use Change, Peat Emissions, and Life-Cycle Greenhouse-Gas Balances to improve this research and add more insights for both the author and readers

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