

Review Article

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Designing Land Use for Climate Mitigation: When and How Oil Palm Plantations Can Contribute to Carbon Emission Reduction

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ABSTRACT

Oil palm has become emblematic of tropical land-use change, often associated with deforestation and greenhouse gas (GHG) emissions. At the same time, emerging biophysical and policy research indicates that oil palm is a highly productive perennial crop with a substantial capacity to sequester and store carbon under appropriate land-use configurations and management regimes. This article develops a qualitative narrative literature review to synthesize recent evidence (primarily from 2020 to 2026) on the conditions under which oil palm plantations can contribute to net carbon emissions reduction within broader land-use planning frameworks. The review integrates biophysical studies on net primary production and carbon stocks with life-cycle assessment and analyses of land-use change, spatial planning, and climate policy, with a specific focus on Indonesia, the world's largest palm oil producer. The findings indicate that oil palm's mitigation contribution is conditional on (i) the initial land cover and land-use history, (ii) site biophysical characteristics (mineral versus peat soils), (iii) adoption of low-emission management and processing technologies, and (iv) alignment with low-carbon spatial planning and agrarian governance. When oil palm replaces degraded lands rather than natural forests or peatlands and is managed with best practices, the net greenhouse gas balance moves towards a carbon sink rather than a source. The article concludes with policy recommendations for land-use planning, regulation, and monitoring to enable oil palm development to support national climate targets while sustaining its economic and rural development roles.

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has also been linked to deforestation, peatland drainage, and associated emissions, especially in Sumatra, Kalimantan, and Papua [2].

JEL Classification: Q15 ; Q24 ; Q28 ; Q54 ; O13 ; Q56

Introduction

Background

Land-use change and agriculture are central to the global greenhouse gas profile, particularly through the Agriculture, Forestry and Other Land Use (AFOLU) sector. Recent assessments estimate that AFOLU accounts for roughly one-fifth of net anthropogenic GHG emissions, with land-use change and deforestation as dominant sources in many tropical regions. The conversion of forests, peatlands, and other carbon-rich ecosystems to cropland and pasture releases large amounts of carbon stored in biomass and soils, creating long-lived "carbon debts" that can take decades or centuries to repay, even under high-productivity land covers [1].

Indonesia exemplifies these dynamics. As a megadiverse tropical country and a major agricultural producer, it has extensive forest and peatland resources alongside the rapid expansion of commodity crops, most prominently oil palm. Palm oil plays a pivotal role in Indonesia's economy, generating export revenues, contributing to rural livelihoods, and supplying feedstock for domestic biodiesel mandates (B30–B35), which form part of the national energy transition strategy. However, oil palm expansion

At the same time, oil palm is a perennial, high-biomass crop with a high net primary production (NPP) and strong photosynthetic performance. Recent research indicates that, under certain conditions, oil palm plantations can sequester large quantities of carbon in aboveground and belowground biomass and may function as net carbon sinks over most of their cultivation cycle, particularly when established on degraded mineral soils and when managed with low emission practices. These findings suggest that the climate implications of oil palm are not inherent to the crop itself but depend strongly on land-use trajectories and management choices [3].

Indonesia's legal and policy framework on land and space further underscores the centrality of land-use planning. The concepts of "tata guna tanah" (land use) and "tata ruang" (spatial planning) have deep roots in agrarian law, originating in the Basic Agrarian Law (UUPA 1960) and later codified in Law 26/2007 on Spatial Planning. These frameworks, together with environmental legislation, define how land is allocated, used, and protected, including through state control over land use, land-use planning, and environmental management. Spatial planning thus provides a key lever for steering agricultural expansion, including oil palm expansion, in ways compatible with low-carbon development [4].

Research Problem and Gap

The global discourse on oil palm and climate change has been dominated by studies emphasizing negative outcomes, particularly those focusing on the conversion of primary forests and peatlands. These studies provide compelling evidence of large committed emissions and long payback times when oil palm replaces high-carbon ecosystems. However, emerging evidence indicates more diverse outcomes when oil palm is cultivated on degraded lands or secondary vegetation, and when advanced low-emission technologies are deployed in processing facilities [5].

Despite this evolving evidence base, conceptual and empirical gaps remain. First, there is limited integrative analysis that explicitly links land-use planning choices- “where” oil palm is planted and “what” land covers it replaces-to the resulting carbon balances across the plantation life cycle. Many carbon accounting and life cycle assessment (LCA) studies treat land-use change parameters as fixed or scenario-based rather than embedded in explicit spatial planning and agrarian governance contexts [6].

Second, the literature is fragmented across disciplinary lines. Biophysical studies of NPP, carbon stocks, and soil emissions are often disconnected from research on spatial planning, agrarian law, and land governance in Indonesia. This fragmentation hampers the development of a coherent narrative explaining under which conditions oil palm can be aligned with national and global climate mitigation objectives [7].

Third, there is a lack of qualitative syntheses that bring together these diverse strands of evidence into a coherent conceptual framework. Systematic reviews have been conducted on related topics, but they typically emphasize quantification and exhaustiveness rather than interpretive integration of biophysical and governance dimensions [1].

Objectives and Research Questions

This article addresses these gaps through a qualitative, narrative literature review focusing on the intersection of land-use planning and the carbon implications of oil palm plantations, with particular attention to Indonesia.

The overarching objective is to develop a conceptual synthesis of the conditions under which oil palm plantations can contribute to net carbon emission reduction through appropriate land-use configurations and management.

To operationalize this objective, the article addresses the following research questions:

- How do land-use planning and agrarian governance frameworks shape trajectories of land-use change involving oil palm plantations in Indonesia? [4].
- Under what biophysical and historical land-use conditions do oil palm plantations exhibit net carbon sink characteristics, as opposed to net emission sources? [8].
- Which management practices and technological interventions most strongly influence the greenhouse gas balance of oil palm production systems? [9].
- How can the emerging empirical evidence be synthesized into a conditional narrative that positions oil palm as potentially contributing to climate mitigation under well specified land-use and governance conditions?

Expected Contributions

The article seeks to make three main contributions. Conceptually, it

proposes a framework that links land-use trajectories, biophysical performance, and governance arrangements to net carbon outcomes in oil palm landscapes. Empirically, it consolidates recent evidence (primarily post-2020) on carbon stocks, emissions, and mitigation potentials in oil palm systems across different land types. Policy-wise, it derives principles and recommendations for land-use planning and regulation that can enable oil palm to support Indonesia’s Nationally Determined Contribution (NDC), Long-Term Strategy for Low Carbon and Climate Resilience (LTS LCCR), and Forestry and Other Land Use (FOLU) Net Sink 2030 targets [10].

Literature Review

Land Use, Land-Use Change, and Carbon Dynamics

The AFOLU sector plays a dual role as both a source and sink of GHGs. On the one hand, deforestation, peatland drainage, and the conversion of grasslands to croplands generate large CO₂ emissions. On the other hand, forests, agroforestry systems, and perennial crops sequester carbon in biomass and soils, offering mitigation potential if protected or enhanced [11].

Recent global assessments emphasize that land-use change is a major driver of GHG emissions and that trajectories of land conversion in tropical regions critically shape the feasibility of achieving global climate targets. Land-use change from natural forest to cropland or pasture often entails a steep loss of carbon stocks. In contrast, conversion of low-biomass degraded lands to tree crops can increase total carbon storage over time [12].

Within this broader context, land-use planning and spatial planning have been recognized as key instruments for climate mitigation. Spatial planning can steer development away from high-carbon ecosystems, concentrate agricultural expansion on lower-carbon lands, and designate conservation areas to maintain or enhance carbon sinks. These principles underpin the notion of “low carbon spatial planning”, which seeks to align land allocation with climate and development goals [13].

In Indonesia, the legal framework for land and space is rooted in the Basic Agrarian Law (UUPA 1960), which establishes the state’s authority to regulate land allocation, use, and conservation for the greatest prosperity of the people. Subsequent legislation, especially Law 26/2007 on Spatial Planning and Law 32/2009 on Environmental Protection and Management, elaborates procedures for spatial planning at national, provincial, and district levels, including the designation of forest areas and non forest areas, zoning for agriculture, settlements, and industry, and environmental safeguards. This system provides the institutional foundation for managing oil palm land-use change [4].

Biophysical Carbon Dynamics of Oil Palm Plantations

Oil palm (*Elaeis guineensis*) is a highly productive tropical crop. Recent work by Murphy synthesizes evidence on carbon sequestration by tropical trees and crops, presenting oil palm as a case study. Oil palm plantations exhibit high gross and net primary production, with NPP values that can match or exceed certain types of tropical forests over significant portions of the plantation cycle. This high productivity reflects efficient photosynthesis, year round growth, and the perennial nature of the crop, which maintains continuous canopy cover and biomass accumulation [3,14-16].

Empirical studies in Southeast Asia have quantified carbon stocks in oil palm plantations on both mineral and peat soils. On mineral soils, mature plantations commonly maintain substantial

aboveground biomass (trunks, fronds, fruit bunches) and root biomass, contributing to significant carbon stocks. Newer studies using field measurements and remote sensing have estimated carbon stocks across plantation ages, often finding increasing biomass carbon until the replanting phase [17].

On tropical peatlands, the situation is more complex. Studies measuring soil CO₂ emissions and NPP in oil palm plantations on drained peat report high NPP but also persistent soil emissions due to peat oxidation, which can offset or exceed biomass sequestration. New research has begun to assess the potential of rewetting peatland oil palm (raising water tables and blocking drainage canals) to reduce soil CO₂ emissions while maintaining some level of production, suggesting significant mitigation potential relative to fully drained systems [18].

Overall, biophysical evidence indicates that oil palm has a strong capacity to sequester carbon in biomass, especially on mineral soils and under good management. The net climate effect, however, depends on the initial land cover and land-use history, as well as soil type and management practices [19].

Land-Use Change Pathways and Oil Palm

The climate impact of oil palm expansion is highly sensitive to what it replaces. Early influential studies showed that conversion of primary forests and peatlands to oil palm generates high committed carbon emissions and long “carbon payback times”. More recent work reinforces that conversion of intact forests and peat domes to new plantations leads to very high CO₂ emissions from both biomass removal and long-term peat oxidation, often outweighing potential sequestration over multiple decades [20].

By contrast, when oil palm replaces low carbon land covers such as grasslands, scrublands, or degraded lands, net carbon stocks can increase over time. Empirical work in Indonesia and other tropical regions shows that plantations established on degraded mineral soils tend to raise total biomass carbon relative to the pre-existing condition, especially when combined with good soil and biomass management practices. Under such trajectories, the crop’s high productivity and perennial nature can contribute to net sequestration, particularly when life-cycle emissions from processing and transport are managed [21].

Peatlands demand special attention. Characteristics of CO₂ and CH₄ emissions from oil palm peatlands have been studied across various locations, revealing substantial soil emissions from drained peat. However, new studies demonstrate that rewetting peatland oil palm concessions-through canal blocking and water table management-reduces soil CO₂ emissions and can significantly lower the net GHG balance. While rewetted peatland plantations typically cannot match the carbon performance of restored forests, they can offer a “transition pathway” that is substantially better than business-as-usual drainage and ongoing peat subsidence [22].

Life Cycle Assessment and Processing Emissions

Beyond land-use change and field emissions, the carbon footprint of palm oil products is influenced by processing and transport stages. Life cycle assessment (LCA) studies have evaluated greenhouse gas emissions from crude palm oil (CPO) and palm biodiesel, often comparing them against fossil fuel benchmarks [23].

A consistent finding is that methane emissions from palm oil mill effluent (POME) are a major contributor to the product’s GHG footprint. LCA studies show that installing methane-capture

(biogas) systems at palm oil mills and using the captured gas for on-site energy generation can substantially reduce total product-related emissions, often by more than half compared with systems without methane capture. Additional reductions arise from using empty fruit bunches and other residues as biomass fuel, improving energy efficiency, and optimizing logistics [24].

When land-use change emissions are low (e.g., plantations on degraded mineral land rather than primary forests or peat) and advanced processing technologies are deployed, the overall GHG intensity of palm biodiesel can fall well below that of fossil diesel, even when accounting for indirect emissions. These results underpin arguments that palm oil-based biofuels can contribute to climate mitigation, provided feedstock production is decoupled from high carbon land conversion [25].

Policy, Governance, and Spatial Planning

Biophysical factors do not solely determine the environmental outcomes of oil palm expansion; they are shaped by land governance, agrarian law, and spatial planning. Indonesia’s spatial planning system is a critical determinant of where oil palm may be legally developed. It distinguishes between forest areas and non forest areas (Areal Penggunaan Lain, APL) and defines permissible land uses through regional spatial plans (RTRW) [4].

In practice, mismatches between formal spatial plans, legal forest designation, and actual land use have been documented. Some areas classified as “forest” lack forest cover, while oil palm plantations exist in zones designated as forest or on peatlands where conversion is legally or environmentally problematic. Such inconsistencies complicate carbon accounting and undermine efforts to align oil palm development with climate goals [7].

In response, Indonesia has adopted several policy instruments, including moratoria on new licenses for primary forests and peatlands, peat restoration programs, and initiatives to direct agricultural expansion towards degraded lands. The country’s Long-Term Strategy for Low Carbon and Climate Resilience (LTS LCCR) and its FOLU Net Sink 2030 strategy explicitly recognize the need to manage land-use change and enhance terrestrial sinks to meet climate targets. Oil palm, as a key land use, is thus implicated in these strategies and can either facilitate or hinder their realization depending on spatial allocation and management practices [26].

Methodology: Qualitative (Narrative) Literature Review Qualitative / Narrative Review Approach

This article adopts a qualitative, narrative literature review approach rather than a systematic review. Narrative reviews are characterized by flexible, interpretive synthesis that integrates evidence from diverse disciplines and methods, with a focus on conceptual development and thematic understanding rather than exhaustive coverage or formal meta-analysis [27].

Such an approach is appropriate for the present topic for several reasons. First, research on oil palm, land use, and carbon spans multiple fields-biogeochemistry, remote sensing, law, policy studies, and economics-each employing different methods and reporting standards. A rigid, systematic protocol risked excluding important sources that do not meet narrow criteria. Second, this article aims to articulate a conditional, integrative narrative about when and how oil palm can contribute to emission reduction, which requires interpretive synthesis across different evidence types. Third, the policy-relevant nature of the topic warrants the incorporation of grey literature from reputable institutions (e.g.,

national climate strategies, FAO, and WRI reports), which are often not captured in conventional systematic review frameworks [10].

The epistemological stance of this review is interpretivist. The objective is not to produce a singular numerical estimate of oil palm's global GHG footprint but to interpret how different studies, using different assumptions and methods, converge or diverge on the conditions under which oil palm functions as a net sink or net source. The analysis, therefore, emphasizes context, assumptions, and governance conditions alongside quantitative results [28].

Literature Search and Selection

The literature search targeted peer-reviewed journal articles and selected policy documents published primarily between 2020 and 2025, complemented by earlier, foundational studies where essential. Searches were conducted using databases such as Scopus and Web of Science, complemented by Google Scholar and Indonesian journal portals. Search strings combined terms related to oil palm, land use, carbon, greenhouse gases, and policy (for example: "oil palm carbon sequestration 2020", "oil palm peatland emissions rewetting", "palm oil life cycle assessment greenhouse gas", "spatial planning low carbon Indonesia") [2].

Inclusion criteria were: (i) relevance to carbon stocks, greenhouse gas emissions, or life cycle impacts of oil palm plantations; (ii) relevance to land-use change involving oil palm or spatial/land-use planning affecting oil palm development; and/or (iii) relevance to methodologies of qualitative or narrative literature review. Articles focusing solely on biodiversity or social impacts without carbon-related content were excluded, except where they provided critical context for land use governance [29].

Priority was given to articles in reputable international journals (e.g., Agriculture, Science of the Total Environment, Global Change Biology) and accredited national journals, as well as to recent policy documents, such as Indonesia's LTS LCCR and FOLU Net Sink strategy. Classic pre-2020 contributions on land-use change and oil palm emissions were selectively included where necessary to contextualize more recent findings [1].

Data Extraction and Thematic Synthesis

Data extraction focused on extracting information relevant to four thematic domains: (i) land use trajectories and initial land cover; (ii) biophysical performance of oil palm systems (NPP, carbon stocks, soil emissions); (iii) management practices and processing technologies; and (iv) governance, spatial planning, and policy instruments. Each selected study was read in full and coded according to these domains [30,31].

Thematic analysis proceeded iteratively. Initial coding informed the development of broad themes, including "oil palm on degraded lands", "oil palm on peatlands and rewetting", "LCA and methane capture", and "spatial planning and moratoria". As additional studies were incorporated, themes were refined, and sub themes were identified (for example, "canal blocking in peat estates", "Forest vs non forest classification conflicts", "traceability and MRV for palm oil emissions") [6].

Narrative synthesis involved comparing findings across studies within and across themes, identifying patterns of convergence and divergence, and relating these to underlying assumptions and contexts. For example, differences in conclusions about oil palm's net climate impact were often traceable to differences in assumptions about prior land cover, peat depth, or inclusion of

methane capture in LCA boundaries. The final synthesis integrates these insights into a conditional narrative that specifies the circumstances under which oil palm can function as a net carbon sink [32,33].

To enhance rigor, the review used transparent inclusion criteria, documented search strategies, and engaged in reflexive consideration of potential biases, including the politicized nature of the palm oil debate. The qualitative, interpretive character of the review is acknowledged as both a strength (allowing cross disciplinary integration) and a limitation (precluding quantitative meta analysis of effect sizes) [34].

Findings

Biophysical Potential of Oil Palm as a Carbon Sink

A consistent message from recent biophysical research is that oil palm is a highly productive carbon-assimilating system under suitable conditions. Murphy's synthesis of tropical trees and crops reports that oil palm exhibits NPP values comparable to or greater than many woody perennials, driven by high photosynthetic efficiency and year round growth in humid tropical climates. These high NPP values translate into rapid biomass accumulation in trunks, fronds, and fruit, and thus substantial carbon sequestration [3].

Field-based studies in Indonesia and elsewhere confirm substantial biomass carbon stocks in mature oil palm plantations. Studies using allometric equations and plot measurements report increasing aboveground biomass up to plantation maturity, with notable contributions from trunk thickening and root development. Remote sensing-based assessments further corroborate these trends at the landscape scale, showing that, on mineral soils, mature oil palm typically stores more aboveground carbon than degraded grassland or shrubland it often replaces [35].

Net ecosystem carbon balance over the plantation life cycle depends on the interplay between biomass accumulation and losses (for example, through harvesting, residue decomposition, and soil emissions). Several recent studies argue that when established on mineral soils with low initial carbon stocks and managed with good practices, oil palm plantations can act as net carbon sinks annually for most of their productive cycle. This conclusion is supported by findings of positive net ecosystem production and long periods where NPP exceeds respiratory and harvest-related carbon outputs [14].

These findings do not negate the high emissions associated with converting carbon rich forests or peatlands, but do suggest substantial mitigation potential where oil palm development is directed towards lower carbon land categories and supported by management that conserves soil organic carbon and minimizes unnecessary biomass burning or disturbance [19].

Importance of Initial Land Cover and Land-Use History

The initial land cover and land use history fundamentally shape the carbon implications of oil palm expansion. Studies focusing on the conversion of primary forests and peatlands in Indonesia document very high emissions from biomass clearing and peat oxidation, often exceeding several hundred tonnes of CO₂ per hectare over decades. Such conversions create large carbon debts that are difficult to repay, even under high NPP oil palm, because the pre existing carbon stocks in forests and peat are so large [36].

By contrast, when oil palm replaces degraded lands, such as along grasslands, scrub, or severely degraded former agricultural

lands, the net effect on carbon stocks can be positive. Several studies show that biomass carbon in such degraded lands is relatively low, and conversion to oil palm leads to a net increase in carbon stored in vegetation, especially when accompanied by improvements in soil management. Under these conditions, the plantation's strong carbon uptake can exceed the initial losses from land preparation, resulting in a positive change in carbon stocks at the plot scale [17].

In peatland contexts, recent research emphasizes that conventional drained oil palm plantations are typically net GHG sources, despite high NPP, because oxidation of peat emits large amounts of CO₂ and, in some cases, N₂O. However, new work on rewetting peatland oil palm suggests significant mitigation potential. Experimental studies show that raising the water table and blocking drainage canals can markedly reduce soil CO₂ emissions while maintaining acceptable yields, shifting the net GHG balance in a more favorable direction, although not fully matching restored forest conditions [18,37].

The key implication is that oil palm's climate role is not monolithic. When plantations replace intact forests or deep peat, they are associated with large net emissions; when they replace degraded mineral soils, they can contribute to net sequestration; and when peatland plantations are rewetted, significant emission reductions are possible relative to current drained systems [22].

Management Practices and Technological Interventions

Management practices at the plantation and mill levels significantly influence the net GHG profile of oil palm systems. At the field level, good agricultural practices-such as balanced fertilization, retention and mulching of pruned fronds, maintenance of ground cover, and minimization of burning-help conserve soil organic carbon and reduce nitrous oxide emissions. Practices that conserve biomass on site (for example, leaving empty fruit bunches in the field as mulch) also enhance soil carbon stocks and may reduce the need for synthetic fertilizers, thereby lowering upstream emissions [12].

At the processing level, LCA studies consistently identify methane emissions from POME as a major hotspot in the GHG footprint of palm oil. When POME is left untreated in open lagoons, anaerobic decomposition releases methane, which has a high global warming potential. Installation of biogas capture systems, combined with the combustion of captured methane for electricity or heat, can drastically reduce these emissions. Several studies report that implementing POME methane capture and biomass-fueled cogeneration at mills can reduce overall GHG intensity of CPO and biodiesel by more than half, and in some scenarios by over 80%, relative to systems without such technologies [38].

When these technological interventions are combined with favorable land-use histories-such as plantations on degraded mineral soils without peat-LCA results show that palm biodiesel can deliver substantial GHG savings relative to conventional diesel. This is particularly salient for countries like Indonesia, where biodiesel policies are central to renewable energy strategies and where improvements in the palm oil value chain could yield large emissions reductions while sustaining domestic energy security [23].

Governance, Land-Use Planning, and Spatial Allocation

Governance arrangements and spatial planning critically determine whether oil palm expansion follows high-emission or low-emission trajectories. Indonesia's spatial planning framework, grounded in

agrarian law and environmental legislation, establishes formal land-use zones and forest-versus-non-forest classifications. In principle, this system can guide oil palm development away from high-carbon ecosystems and towards lands where net carbon gains are likely [4,39-42].

However, empirical analyses reveal persistent mismatches between formal designations, actual land cover, and land use. Some areas legally designated as "forest" have little or no forest cover. At the same time, oil palm and other uses occur within administrative forest boundaries or on peatlands where conversion is environmentally risky. These discrepancies undermine clarity in governance and complicate efforts to account for and regulate emissions from land-use change [20,43-46].

To address these issues, Indonesia has introduced several policy instruments that directly affect the oil palm's role in the climate. Moratoria on new licenses for primary forest and peatland conversion aim to prevent further expansion into the highest-carbon ecosystems. Peat restoration and rewetting programs aim to reduce emissions from existing drained peatlands, including those under oil palm cultivation. Agrarian reform initiatives (TORA) and spatial reallocations open possibilities for channeling future plantation development towards degraded lands with lower carbon stocks and higher potential for net sequestration [47].

Internationally driven sustainability standards, such as RSPO and Indonesia's own ISPO, together with traceability and carbon accounting tools (for example, PalmGHG), further encourage alignment of plantation siting and management with climate objectives by linking market access and reputational benefits to adherence to environmental and social criteria. These schemes increasingly incorporate requirements related to high conservation value (HCV) areas, high carbon stock (HCS) approaches, and no deforestation commitments, all of which directly intersect with land-use planning [48].

Towards a Conditional Narrative

The literature reviewed supports a nuanced, conditional narrative on oil palm and climate. On one side, studies of deforestation and peatland conversion document significant emissions associated with past and some ongoing expansion, especially where oil palm replaces intact forests or deep peat. On the other side, biophysical, LCA, and governance studies illustrate a pathway whereby oil palm can function as an efficient carbon sink and low carbon feedstock under specific land-use and management conditions [49].

The central insight is that oil palm is neither inherently "good" nor "bad" for the climate. Rather, its net impact is contingent on:

- Initial land cover and land-use history (forest/peat vs degraded land);
- Site characteristics (mineral vs peat soils, depth of peat, hydrology);
- Management and technology (good agricultural practices, methane capture, biomass energy use); and
- Governance and spatial planning (enforcement of no deforestation rules, prioritization of degraded lands, effective MRV).

When these conditions are aligned, oil palm can contribute to net carbon emission reduction while supporting rural livelihoods and energy security. When they are not, oil palm can be a major driver of land use emissions.

Discussion

Scale and Time Horizons in Assessing Oil Palm's Climate Role Assessments of oil palm's climate impact frequently differ because they operate at different scales and time horizons. Plot-level studies of mature plantations on mineral soil typically report positive net carbon balances and substantial carbon stocks relative to degraded baselines. Landscape-level analyses that incorporate a mosaic of land uses, including remaining forests, peatlands, and non-planted areas, often reveal more complex outcomes, including substantial emissions from peat and residual deforestation [8].

Time horizon matters as well. Immediate emissions from forest clearing or peat drainage occur rapidly, whereas sequestration in planted biomass accrues over years or decades. Short-term assessments emphasizing initial land-clearing emissions may conclude that oil palm is a large net source, whereas longer-term perspectives may recognize eventual carbon stock recovery or net gains under favorable conditions. However, where initial carbon stocks are extremely high, as in deep peat, payback times may be so long as to be incompatible with urgent climate objectives [50].

Recognizing these scales and temporal dynamics is crucial. A fair assessment of oil palm's potential contribution to climate mitigation must distinguish between historical legacy emissions (which need to be addressed through restoration and rewetting) and forward-looking scenarios that could reorient expansion towards lower carbon trajectories.

Land-Use Planning as a Lever for Decoupling Oil Palm from Deforestation

Land-use planning stands out as a practical and powerful lever to ensure that future oil palm development aligns with climate mitigation. Low-carbon spatial planning involves designating and enforcing zones where new plantations are acceptable (e.g., degraded APL lands with low carbon stocks) and where they are not (e.g., primary forests, peat domes, key biodiversity areas) [13,51-54].

In the Indonesian context, aligning spatial plans, forest zoning, and actual land cover is a prerequisite. This includes updating forest area maps to reflect current conditions, clarifying the status of non-forest lands suitable for agriculture, and ensuring that regional spatial plans integrate national climate goals, including the FOLU Net Sink 2030 target. Incorporating high-carbon-stock and high-conservation-value mapping into formal planning processes would further help differentiate acceptable from unacceptable expansion zones [10].

Land swap mechanisms and moratoria can support this realignment by enabling the gradual relocation of planned or existing plantations from high-carbon areas to lower-carbon alternatives, while compensating landholders and ensuring legal clarity. For existing peatland plantations, integrating rewetting and improved water management into spatial planning, combined with clear guidance on long-term land-use trajectories, can significantly reduce emissions and create space for phased ecological restoration where feasible [22].

By explicitly integrating carbon considerations into spatial planning, policymakers can harness oil palm's high productivity and carbon assimilation capacity while minimizing adverse land use change emissions.

Policy Implications for Indonesia's Climate and Development Strategy

Indonesia's climate strategies, including its NDC, LTS LCCR, and FOLU Net Sink 2030, rely heavily on land-based mitigation. These strategies aim to reduce deforestation, enhance forest and land sinks, and manage peatlands more sustainably. Oil palm's future trajectory will significantly influence the success of these goals [26].

From a policy perspective, three broad implications emerge from the reviewed literature.

First, directing new oil palm development to degraded mineral lands, combined with clear protection of remaining primary forests and deep peat, offers a tractable pathway to maintain or increase agricultural production while limiting land use emissions. Such a strategy would capitalize on oil palm's high NPP and carbon sequestration potential in appropriate contexts [21].

Second, accelerating the adoption of low-emission practices and processing technologies—especially methane capture from POME and biomass-based energy at mills—can substantially improve the life cycle GHG profile of palm oil products. These measures align well with energy policy objectives and could yield co-benefits, including reduced local air pollution and improved energy security [9].

Third, strengthening monitoring, reporting, and verification (MRV) systems for land use emissions and sinks, including those associated with oil palm, is crucial. Integrating remote sensing, field inventories, and traceability tools can improve the accuracy of carbon accounting and bolster confidence in claims about low-emission or net sink palm oil. More transparent MRV systems can also support participation in international climate finance or carbon market mechanisms [55].

Methodological Reflections and Research Needs

The qualitative, narrative nature of this review allows for the integration of diverse evidence, but it does not provide a quantitative meta-analysis of effect sizes or definitive numerical thresholds for "safe" oil palm expansion. This limitation suggests several directions for further research.

There is a need for more long-term, integrated studies that combine field measurements of carbon stocks and fluxes with explicit documentation of land-use history, management practices, and policy context. In peatland systems, more research on the long term performance of rewetted oil palm plantations, including yield, soil emissions, and hydrological impacts, would clarify the viability of transition pathways that balance production with mitigation [18].

Scenario modeling linking spatial planning options, agrarian reforms, and plantation development trajectories to national carbon budgets could provide quantitative insights into how different land-use strategies affect Indonesia's ability to meet its climate targets. Integrating socio-economic dimensions—including impacts on smallholders, labor, and local communities—into carbon-focused analyses would further ensure that proposed pathways are equitable and politically feasible [29].

Finally, methodological work on qualitative and integrative literature reviews in environmental and land-use research could strengthen the rigor and transparency of future syntheses [56-59].

Conclusion and Policy Recommendations

Substantive Conclusions

This article examines the conditions under which oil palm plantations can contribute to net carbon emission reductions within the context of land-use planning and governance, with a particular focus on Indonesia. The key conclusion is that the oil palm's climate role is fundamentally conditional.

Oil palm has a high capacity for carbon assimilation and can maintain substantial biomass carbon stocks, especially on mineral soils under good management. When plantations are established on degraded lands with low initial carbon stocks and managed with practices that conserve soil carbon and avoid burning, the net effect on carbon sequestration can be positive. When processing facilities adopt methane capture for POME and use biomass residues for energy, the life-cycle GHG intensity of palm oil products can be substantially lower than that of fossil fuels, thereby enhancing their role in low-carbon energy strategies.

Conversely, where oil palm expansion involves conversion of primary forests or deep peatlands, large committed emissions and long carbon payback times make such trajectories incompatible with near term climate mitigation needs. In these cases, even the crop's high NPP cannot offset the magnitude of initial carbon losses within relevant policy timeframes.

Therefore, oil palm can be a meaningful contributor to climate mitigation only under specific, well defined conditions: (i) siting on degraded lands or low carbon mineral soils; (ii) avoidance of new conversion of primary forests and deep peat; (iii) adoption of low emission management and processing technologies; and (iv) alignment with robust, low carbon spatial planning and governance frameworks.

Policy Recommendations for Land-Use Planning and Governance
To operationalize these insights, several policy recommendations can be articulated.

First, formal spatial planning processes at national and subnational levels should systematically integrate carbon considerations by mapping high-carbon-stock and high-conservation-value areas, updating forest and peatland designations to reflect current conditions, and designating priority zones for agricultural expansion on degraded lands. This includes enforcing existing moratoria on primary forest and peat conversion and aligning sectoral plans (for agriculture, energy, and infrastructure) with low-carbon land use strategies.

Second, regulatory and economic instruments should be deployed to accelerate the adoption of low-emission practices and technologies. This may include fiscal incentives or concessional finance for POME methane capture and biomass-based cogeneration, support for rewetting peatland plantations, and performance-based payments linked to verifiable emissions reductions in oil palm landscapes.

Third, MRV systems for land use emissions and sinks must be strengthened. Integrating satellite monitoring, field inventories, and supply chain traceability would improve transparency and enable more accurate attribution of emissions and removals to specific land uses and management regimes. Such systems would support the implementation of domestic policy and bolster Indonesia's position in international markets and climate negotiations.

Implications for International Debates and Indonesia's Positioning
The conditional narrative articulated here has implications for international debates around palm oil. It suggests that blanket characterizations of palm oil as uniformly harmful to the climate overlook significant mitigation opportunities when development is steered towards appropriate land types and accompanied by advanced low-emission practices. At the same time, it confirms that converting high-carbon ecosystems to oil palm is incompatible with climate goals and should be avoided.

For Indonesia, aligning oil palm governance with global climate and sustainability regimes presents both a challenge and an opportunity. By demonstrating credible progress in decoupling oil palm from deforestation and peat conversion, improving the carbon performance of existing plantations, and enforcing robust MRV and traceability systems, Indonesia can strengthen its bargaining position in trade and climate negotiations while supporting domestic development objectives.

Finally, oil palm can be part of climate solutions if-and only if-land-use planning, governance, and management choices are deliberately oriented towards low-carbon trajectories. Recognizing and institutionalizing this conditionality provides a pragmatic basis for reconciling economic reliance on palm oil with the imperatives of climate mitigation.

References

1. Li L, Awada T, Shi Y, Jin VL, Kaiser M (2025) Global Greenhouse Gas Emissions from Agriculture: Pathways to Sustainable Reductions. *Glob Chang Biol* 31: e70015.
2. Traction Energy Asia (2019) Greenhouse Gas Emissions from Biodiesel Production in Indonesia Based on Life Cycle Analysis, Jakarta, 2019. https://tractionenergy.asia/wp-content/uploads/2019/10/LCA_Biodiesel_English.pdf.
3. Murphy DJ (2024) Carbon Sequestration by Tropical Trees and Crops: A Case Study of Oil Palm. *Agriculture* 14: 1133.
4. Samadhi N (2026) Spatial Planning for Low Carbon Development in Indonesia WRI Indonesia Insights: Food, Land, and Water Indonesia. <https://wri-indonesia.org/en/insights/spatial-planning-low-carbon-development-indonesia>.
5. Carlson KM, Lisa M Curran, Dessy Ratnasari, Alice M Pittman, Britaldo S Soares-Filho, et al. (2012) Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia. *Proc. Natl Acad Sci* 109: 7559-7564.
6. Hong WO (2023) Review on Carbon Footprint of the Palm Oil Industry: Insights into Recent Developments. *Int J Sustain Dev Plan* 18: 447-455.
7. Magfoedin M, Soemarno S, Atikawati D (2025) Spatial Analysis of the Land Object of Agrarian Reform Redistribution Priorities for Supporting Low Carbon Development. *BHUMI J Agrar dan Pertanah* 11: 138-161.
8. Siallagan EJ, Siregar YI, Nofrizal N, Ismail UP (2025) Engineering carbon dynamics and vegetation indices in oil palm plantations: An integrated assessment of carbon stocks, normalized difference vegetation index, and net ecosystem exchange in Riau Province. *J Ecol Eng* 26: 342-349.
9. De Rosa M, Schmidt J (2022) Life Cycle Assessment of Palm Oil at United Plantations Berhad 2022. Teluk Intan Malaysia. <https://lca-net.com/files/Life-Cycle-Assessment-of-Palm-Oil-at-United-Plantations-Berhad-2022.pdf>.
10. (2021) Government of Indonesia Indonesia Long-Term Strategy for Low Carbon and Climate Resilience 2050 (Indonesia LTS-LCCR 2050). Jakarta https://unfccc.int/sites/default/files/resource/Indonesia_LTS-LCCR_2021.pdf.

11. Huang S, Samane Ghazali, Saghi Movahhed Moghaddam, Ants-Hannes Viira, Kristina Janečková, et al. (2023) Contribution of agricultural land conversion to global GHG emissions: A meta-analysis. *Sci Total Environ* 876: 162269.
12. Abreu NL, Eleanatan Syanne da Cruz Ribeiro, Camila Eduarda Souza de Sousa, Lorena Maués Moraes, João Victor Costa de Oliveira, et al. (2024) Land use change and greenhouse gas emissions: an explanation about the main emission drivers. *Ciência Anim Bras* 25: 15.
13. Fielding D, Matthews R (2014) Review of implications of land use change on climate change mitigation and adaptation. Aberdeen. https://www.climateexchange.org.uk/wp-content/uploads/2023/09/review_of_the_climate_implications_of_land_use_change.pdf.
14. Paterson RRM (2025) Future Scenarios for CO2 Sequestration by Oil Palm in Southeast Asia Versus Other Regions to Reduce Climate Change. *Southeast Asia Dev Res* 1: 47-55.
15. Murphy DJ, Goggin K, Paterson RRM (2021) Oil palm in the 2020s and beyond: challenges and solutions. *CABI Agric Biosci* 2: 1-22.
16. Yosephine IO, Effendi Z, Fitriana D (2025) Study of the Productivity of Oil Palm Plants (*Elaeis guineensis* Jacq.) on Different Topographies. *J Tek Pertan. Lampung (Journal Agric Eng* 14: 1349-1358.
17. Singh SL, Sahoo UK, Kenye A, Gogoi A (2018) Assessment of Growth, Carbon Stock and Sequestration Potential of Oil Palm Plantations in Mizoram, Northeast India. *J Environ Prot (Irvine Calif)* 9: 912-931.
18. Wakhid N, Hirano T (2021) Soil CO2 emissions and net primary production of an oil palm plantation established on tropical peat. *Mires Peat* 27: 13.
19. Wicke B, Sikkema R, Dornburg V, Faaij A (2011) Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. *Land use policy* 28: 193-206.
20. Agus F, Gunarso P, Sahardjo BH, Harris N, van Noordwijk M, et al. (2013) Historical CO2 Emissions from Land Use Change from the Oil Palm Industry in Indonesia, Malaysia, and Papua New Guinea. https://www.tropenbos-indonesia.org/file.php/1344/5_historical_co2_emissions_agus_et_al.pdf.
21. (2023) PASPI Monitor Global Warming and Solutions from the Palm Oil Industry. *J Anal Palm Oil Strateg* 7: 783-790.
22. Novita N, Adibtya Asyhari, Rasis P Ritonga, Adi Gangga, Gusti Z Anshari, et al. (2024) Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands. *Sci Total Environ* 952: 175829.
23. Rinaldo R, Suprihatin S, Yani M (2023) Life cycle assessment produksi crude palm oil (CPO) (studi kasus: PT X Provinsi Bengkulu). *Agrointek J Teknol Ind Pertan* 17: 651-659.
24. PASPI-Monitor (2021) Palm Oil Industry Will Become a Net Carbon Sink. *Palm Oil J Anal Palm Oil Strateg* 2: 575-580.
25. Yee KF, Tan KT, Abdullah AZ, Lee KT (2009) Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability. *Appl Energy* 86: 189-196.
26. (2024) Committee on Agriculture Update on the Guidelines for Integrated Land Use Planning. Rome. <https://openknowledge.fao.org/server/api/core/bitstreams/8e2fc4bc-086d-4294-95ba-f69ce18f03e9/content>.
27. Pare G, Kitsiou S (2025) Methods for Literature Reviews. *Handbook of e-Health Evaluation: An Evidence-based Approach*. <https://www.ncbi.nlm.nih.gov/books/NBK481583/>.
28. Sukhera J (2025) Narrative Reviews: Flexible, Rigorous, and Practical. *J Grad Med Educ* 14: 414-417.
29. Benedict JJ Heilmayr R (2025) Trase: Indonesian palm oil exports and deforestation. SEI <https://www.sei.org/features/indonesian-palm-oil-exports-and-deforestation/>.
30. Snyder H (2019) Literature review as a research methodology: An overview and guidelines. *J Bus Res* 104: 333-339.
31. Snyder H (2024) Designing the literature review for a strong contribution. *J Decis Syst* 33: 551-558.
32. Carlson KM, Robert Heilmayr, Holly K Gibbs, Praveen Noojipady, Douglas C Morton, et al. (2018) Effect of oil palm sustainability certification on deforestation and fire in Indonesia. *Proc Natl Acad Sci* 115: 121-126.
33. Zhang YS, Julio Aleman, Su Ryon Shin, Tugba Kilic (2017) Multisensor-integrated organs-on-chips platform for automated and continual in situ monitoring of organoid behaviors. *Proc. Natl. Acad. Sci* 114: E2293-E2302.
34. Kalpokas N, Radivojevic I (2021) Adapting practices from qualitative research to tell a compelling story: A practical framework for conducting a literature review. *Qual Rep* 26: 1546-1566.
35. Anggraini S, Tampubolon OM, Tiara (2024) Estimated Carbon Stock in Palm Oil Plantations at PT. Sinar Gunung Sawit Raya, North Sumatra. *Agrotekma J Agroteknologi dan Ilmu Pertan* 9: 43-52.
36. Hergoualc'h K, Gonzales ML, 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. *Agric. Ecosyst Environ* 386: 109603.
37. Wakhid N, Hirano T, Dariah A, Agus F (2022) Net primary production of oil palm plantations on tropical peat. *Mires Peat* 28: 02.
38. (2024) GAPKI Studies Show Palm Oil's Big Contribution for Net Carbon Sink. GAPKI Myths & Facts Publication and Recent News. <https://gapki.id/en/news/2024/10/24/studies-show-palm-oils-big-contribution-for-net-carbon-sink/>.
39. Paoli GD, Piers Gillespie, Philip L Wells, Lex Hovani (2013) Oil Palm in Indonesia: Governance Decision Making, & Implications for Sustainable Development - Summary for Policy Makers & Practicioners. Jakarta https://www.researchgate.net/publication/256199165_Oil_palm_in_Indonesia_governance_decision_making_and_implications_for_sustainable_development.
40. Judijanto L (2025) Governance reform in the palm oil sector from upstream to downstream: a review. *Rev Caribeña Ciencias Soc* 14: 4703.
41. Triyanti A, Indrawan M, Nurhidayah L, Marfai MA (2023) Eds Environmental Governance in Indonesia in Environment & Policy Cham: Springer International Publishing. 10.1007/978-3-031-15904-6.
42. Purwanto E, Santoso H, Jelsma I, Widayati A, Nugroho HYSH, et al. (2020) Agroforestry as Policy Option for Forest-Zone Oil Palm Production in Indonesia. *Land* 9: 531.
43. Putri EIK, Arya Hadi Dharmawan, Otto Hospes, Bayu Eka Yulian, Rizka Amalia, et al. (2022) The Oil Palm Governance: Challenges of Sustainability Policy in Indonesia. *Sustainability* 14: 1820.
44. Nahib I, Yudi Wahyudin, Widiatmaka Widiatmaka, Suria Darna Tarigan, Wiwin Ambarwulan, et al. (2026) Spatio-Temporal Dynamics of Land Use and Land Cover Change and Ecosystem Service Value Assessment in Citarum Watershed, Indonesia: A Multi-Scenario and Multi-Scale Approach. *Resources* 15: 24.
45. Giofandi EA, Sekarjati D, Tjahjono B, Hidiya M, Mulyono MR (2025) Long-term land use dynamics and scenario-based planning for sustainable development in the dumai river basin, Western Indonesia. *J Umm Al-Qura Univ Appl Sci*. 10.1007/s43994-025-00296-5.
46. Hernanda TAP, Fauzi A, Barus B, Arifin B, (2026) Land

- cover and socio-economic dynamics of coffee to oil palm land conversion in Way Kanan, Indonesia. *J Degrad Min Lands Manag* 13: 9271-9291.
47. Harmoko HA, Wurarah RN, Pattiasina TF (2024) Building agricultural potential: Utilization of former land use rights by spatial planning. *Soc Ecol Econ Sustain Dev Goals J* 10.61511/seesdgj. v1i2.2024.355.
48. Lan CC, Phillips J (2023) Here are 5 action areas to decarbonize palm oil production. *World Economic Forum: Nature and Biodiversity*. <https://www.weforum.org/stories/2023/06/decarbonizing-palm-oil-industry-net-zero/>.
49. (2023) PASPI Monitor Advantages of Oil Palm Plantations as Carbon Sink and Emission-Efficient Oil Production. *J Anal Palm Oil Strateg* 4: 1-8.
50. Kasak K, Iryna Dronova, Kaido Soosaar, Wong Guan Xhuan, Faustina Sangok, et al. (2025) Greenhouse gas emissions from ditches in oil palm plantations on tropical peatlands in Malaysia. *Sci Rep* 15: 37126.
51. Zhao J, Cochrane M, Lee J, Zhang, Elmore A (2025) Managing sustainable expansion of smallholder oil palms with strategic spatial planning of land use. *J Land Use Sci* 20: 276-288.
52. Siregar SB, Kadaryanto B, Yalid (2026) Implementation of Land Use for Palm Oil Plantations by the Indragiri Hilir Community in the Area Forests through Sustainability Mechanisms Planting According to the Law of Job Creation. *JILPR J Indones Law Policy Rev* 7: 318-332.
53. Andini P, Nurlika R, Salma Y, Wicaksono A (2024) Spatial-Temporal Analysis of Land Cover Change and Oil Palm Expansion in Gunung Mas. *BHUMI J Agrar dan Pertanian* 9: 186-202.
54. Ariesca R, Sau AAWT, Adinugroho WC, Setiawan AAR, Ahamed T, et al. (2023) Land Swap Option for Sustainable Production of Oil Palm Plantations in Kalimantan, Indonesia. *Sustainability* 15: 2394.
55. (2026) Peterson Solutions Palm Oil Goes Green: The Journey Towards Net-Zero Emissions and Lower Carbon Footprint. Peterson Solutions. <https://www.petersonindonesia.com/post/palm-oil-goes-green-the-journey-towards-net-zero-emissions-and-lower-carbon-footprint>.
56. Whitemore R, Knafl K (2005) The integrative review: updated methodology. *J Adv Nurs* 52: 546-553.
57. Menon JML, Struijs F, Whaley P (2022) The methodological rigour of systematic reviews in environmental health. *Crit. Rev Toxicol* 52: 167-187.
58. De Cassai A, Dost B, Tulgar S, Boscolo A (2025) Methodological Standards for Conducting High-Quality Systematic Reviews. *Biology (Basel)* 14: 973.
59. Sarkki S, Mia Pihlajamäki, Katriina Soini, Ann Ojala, Tatiana Kluvankova, et al. (2025) Integrative literature review on co-concepts in connection with nature-based solutions *Environ Sci Policy* 169: 104073.

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