



Peatlands, Oil Palm, and Sustainability in Indonesia: A Review of Hydrological Governance, Environmental Trade-offs, and Socioeconomic Futures

Loso Judijanto
IPOSS Jakarta

Corresponding Author: Loso Judijanto losojudijantobumn@gmail.com

ARTICLE INFO

Keywords : Tropical Peatland, Oil Palm, Sustainability Governance, Water-Table Management, Subsidence, Peat Fire, Greenhouse Gas Emissions, Rewetting, Indonesia

Received : 2 February

Revised : 20 March

Accepted: 18 April

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

Internasional.



ABSTRACT

Tropical peatlands are globally significant carbon stores, but they become highly vulnerable to degradation when drained and cleared for agricultural production, including oil palm cultivation. In Indonesia, oil palm cultivation on peat is both economically consequential and environmentally contested, with central debates focusing on greenhouse gas (GHG) emissions, subsidence, peat fires, biodiversity loss, and the credibility of sustainability governance through standards and regulation. This qualitative literature review synthesizes post-2020 scientific and policy-relevant scholarship alongside foundational Indonesian peat-oil palm discussions to clarify what is known, what remains disputed, and what conditions shape divergent findings. The review applies a thematic synthesis centered on hydrological governance (water-table management, drainage infrastructure, and rewetting/restoration) because it has been consistently positioned that groundwater level (GWL)/muka air tanah (MAT) as the “hinge” connecting local biophysical outcomes (subsidence and fire vulnerability) to global climate claims (CO₂-equivalent emissions). Evidence from recent peer-reviewed studies indicates that the climate impact of peat conversion is strongly time-dependent, with particularly high emissions during early conversion stages and continued net carbon losses through oil palm rotations in many settings. At the same time, recent work also points to substantial mitigation potential from rewetting interventions (e.g., canal blocking) in specific contexts, while warning about implementation constraints and livelihood implications, especially for smallholders. The article concludes by outlining policy and management pathways that treat peatland oil palm sustainability as a problem of risk-governed trade-offs rather than a binary “sustainable/unsustainable” label

INTRODUCTION

Background: Peatlands, Oil Palm, and Sustainability Tensions

Tropical peatlands are a distinct ecosystem type whose long-term stability depends on persistently wet conditions; drainage disrupts this stability by altering peat moisture and decomposition dynamics. It has been emphasized that peatland use for oil palm expanded partly because suitable mineral lands for large-scale commercial development became more limited and land control became more complex, making peat an increasingly selected frontier for investment and smallholder conversion. Oil palm's economic importance—nationally and locally—helps explain why peat debates are rarely only “environmental,” but are also framed as development, trade competitiveness, and livelihood questions [1].

A central theme is the divergence between (a) the global environmental narrative that associates peat oil palm with deforestation, fires, and high GHG emissions, and (b) counter-claims that some accusations exceed observed field realities or rely on overestimated emission calculations. This divergence persists because peat emissions are difficult to quantify consistently and because “sustainability” is mediated by policy instruments (e.g., peat ecosystem rules) and market instruments (e.g., ISPO/RSPO), each with different incentives and enforcement capacities. Recent peer-reviewed measurements show that converting peat swamp forests to oil palm can yield high combined GHG emission factors when CO₂, N₂O, and CH₄ are included, and that emissions vary across conversion phases (drainage stage, young plantation stage, mature stage). Meanwhile, other post-2020 studies indicate that net carbon outcomes may remain strongly negative over a plantation rotation, implying that mitigation strategies should prioritize preventing new peat conversion while improving water governance where peat oil palm already exists [2].

Why is Hydrology Governance the Analytic Center

It has been repeatedly linked key sustainability issues—subsidence, fires, and emissions—to groundwater level (GWL/MAT), suggesting that peatland oil palm sustainability is best interpreted through hydrological governance rather than through single-issue metrics. Hydrology governance matters not only in plantations but across whole peat hydrological units, because drainage canals and water control structures connect multiple land users and can export risk beyond concession boundaries. A significant implication from recent literature is that rewetting (often through canal blocking) can have strong climate-mitigation potential in specific settings, strengthening the argument that water management is the most actionable lever in already-developed peat landscapes [3].

Problem Statement

Despite a large and growing evidence base, there remains no single, widely accepted account of what “sustainable oil palm on peat” means in practice because the literature is fragmented across biophysical science, governance studies, and market/standards research. It also has been highlighted methodological controversies, particularly when subsidence-based estimates are interpreted as direct proxies for emissions without fully accounting for peat compaction and consolidation. These disagreements complicate policy communication, international legitimacy debates, and the design of realistic

mitigation pathways that maintain livelihoods while reducing environmental harm[4].

Objectives and Guiding Questions

This article has three objectives grounded in the structure (issues → management → future direction) and updated with post-2020 peer-reviewed evidence [1].

1. Objective 1: Map dominant post 2020 themes and contested claims in peat-oil palm sustainability debates [5].
2. Objective 2: Synthesize mechanisms linking water-table governance and drainage infrastructure to key outcomes (GHG emissions, fire risk, subsidence, and longer-run viability) [1].
3. Objective 3: Identify plausible pathways for “better-than-status-quo” sustainability transitions in existing peat oil palm landscapes, including rewetting/restoration and governance risk management [6].

Guiding questions:

- How does hydrological management mediate the main environmental impacts attributed to oil palm on peat? [1]
- Which claims are robust across methods and contexts, and which depend strongly on assumptions, system boundaries, and time horizons? [2]
- What governance and livelihood constraints shape the feasibility of rewetting and restoration in real plantation–smallholder mosaics? [4].

LITERATURE RIVIEW

1. Key Concepts Used In This Review

Peat and tropical peatland. It has been discussed that peat as an organic soil (Histosols/Organosols in soil classification traditions). It emphasizes that peatland management must begin with recognition of peat’s unique physical, chemical, and hydrological properties. This review uses “peatland” as a coupled ecological–hydrological system whose functioning depends on water saturation patterns, not simply a soil substrate [7].

Sustainability in oil palm landscapes. Sustainability is presented in a governance sense—compliance, feasibility, environmental management, and social relations—closely aligned with certification framings such as ISPO and RSPO. For this article, sustainability is treated as a multi-criteria outcome across at least four domains: (1) climate/GHG, (2) fire and air quality risk, (3) land stability and long-run viability (subsidence/flood vulnerability), and (4) social-economic legitimacy (livelihoods, trade acceptance, governance credibility) [6]. Hydrological governance. It has been stated repeatedly uses groundwater level (MAT) as an operational indicator tied to emissions, subsidence, and fire risk, implying that sustainability is “governed” through water-control infrastructure and monitoring systems. In post-2020 scientific work, peat rewetting and water-table adjustment are also framed as climate-mitigation interventions, which strengthens the analytical choice to place hydrology governance at the center of a qualitative synthesis [3].

2. Theoretical Lenses To Interpret a Contested Evidence Base

Social-ecological systems and risk governance. Peatlands can be viewed as systems with thresholds: crossing a dryness threshold increases fire susceptibility and accelerates degradation, requiring adaptive management and continuous monitoring. A risk-governance framing is especially appropriate because it does not claim that impacts are absent, but argues that implications can be mischaracterized or overgeneralized, a classic problem of risk communication under uncertainty [7].

Political ecology / political economy of narratives. It has been noted that international campaigns and trade-related pressures surrounding oil palm, suggesting that sustainability debates are shaped not only by measurable outcomes but also by global politics and legitimacy contests. This aligns with a political ecology lens that treats “what counts as evidence” as partly shaped by actor interests, standards, and geopolitical contexts rather than by biophysical measurement alone [8].

Multi-level governance and standards. It has been positioned that ISPO/RSPO and Indonesian regulation as interacting governance instruments that attempt to translate sustainability into enforceable criteria and indicators. Recent restoration scholarship further supports a multi-level lens by describing national-scale restoration potential assessments and risk management processes that rely on multi-actor coordination and spatial planning [3].

3. What Post-2020 Literature Contributes and Why it Matters for Synthesis)

Recent high-impact evidence highlights that the climate consequences of peat conversion are not well captured by “forest vs mature plantation” comparisons alone, because emissions vary substantially across conversion phases and gases. Nature Communications evidence shows that N₂O can contribute materially to combined global warming potential after conversion, and that the conversion process itself can dominate the life-cycle climate impact. Complementing this, findings from Global Change Biology indicate sustained net carbon losses in oil palm plantations converted from logged peat swamp forests, reinforcing the argument that time horizon and baseline condition strongly shape conclusions [2].

At the same time, the post-2020 literature base also expands the solution space by quantifying mitigation potential from rewetting and emphasizing the need for feasibility-aware risk management, rather than presenting restoration as purely technical. Qualitative evidence from PubMed Central-archived research on smallholder perceptions of rewetting in Sumatra suggests that canal blocking and rewetting interventions can have livelihood consequences that must be addressed through complementary livelihood strategies and participatory governance. This is consistent with the emphasis on balancing environmental advocacy with holistic development planning [4].

METHODOLOGY

1. Approach and Rationale

This study uses a qualitative literature review (QLR) approach rather than a systematic literature review, with the goal of interpretive integration: mapping debates, clarifying mechanisms, and identifying boundary conditions that explain why results differ across contexts and methods. A QLR is appropriate here because peat–oil palm sustainability is not only an empirical question (“how large are emissions?”) but also a governance and framing question (“which metrics are privileged, what assumptions underlie them, and which solutions are feasible under real constraints?”). The article is mainly written in a policy-relevant scientific narrative style – moving from issues to standards to technical management to future direction – making it a suitable for an interpretive synthesis rather than a database-exhaustive review [6].

2. Corpus Construction (Transparent, But Not Exhaustive)

The review corpus was assembled through iterative searching and citation chaining around seven thematic clusters: (1) peat definitions and characteristics, (2) oil palm expansion and land-cover change narratives, (3) water-table management and drainage infrastructure, (4) GHG measurement and accounting controversies, (5) fire risk and prevention, (6) subsidence and long-run land viability, and (7) governance through standards and restoration institutions. To strengthen timeliness, the review prioritizes post-2020 peer-reviewed journal articles (Scopus/WoS-indexed outlets where identifiable from publisher venues), including Nature Communications, Science of the Total Environment, Global Change Biology, Scientific Reports, Frontiers journals, and Restoration Ecology. Foundational pre-2020 sources are used selectively to explain definitions and historical debates, but the main interpretive weight is given to 2020–2026 evidence [9].

3. Inclusion and Exclusion Criteria

Included items met at least one of the following criteria: (a) direct measurement or modeling of GHG fluxes or carbon balance in tropical peatland conversion/oil palm contexts, (b) explicit analysis of hydrology governance (water table, drainage, canal blocking, rewetting), (c) evidence on peat fire drivers and severity in Indonesia’s peat landscapes, or (d) peer reviewed governance/restoration risk management analyses with clear relevance to peat oil palm landscapes. Excluded items were opinion-only texts without traceable methods, or sources that could not be verified as credible/traceable for key claims needed in this article. (No citation) [5].

4. Analytic Strategy: Thematic Synthesis

The synthesis followed an iterative thematic analysis: (1) initial code families (hydrology, emissions, subsidence, fire, biodiversity/deforestation narratives, standards, and futures), (2) mapping post 2020 peer reviewed evidence into these code families, and (3) developing integrative themes that explain both convergence and divergence across sources. Particular attention was given to how studies define baselines (e.g., intact peat swamp forest vs logged forest vs degraded shrubland), time horizons (conversion stage vs mature plantation), and system boundaries (CO₂-only vs multi-gas CO₂+CH₄+N₂O;

plantation surface vs drainage ditches), because these choices strongly influence reported outcomes [9].

5. Trustworthiness and Reflexivity

Because peat-oil palm debates are politically charged, reflexive memoing was used to track interpretive risks, such as overgeneralizing from single-site studies or adopting a single narrative frame as default. The analysis also treats strong on Indonesian agronomic and governance framing—while using post-2020 international journal evidence to test, nuance, or triangulate its core claims (e.g., debates over emission magnitudes and mitigation options) [3].

RESULT

1. Theme 1 – Why Peat Conversion Happens (and Why it Persists)

It has been framed that oil palm expansion onto peat as a historically contingent response to land scarcity on mineral soils, the availability of peat landscapes for larger-scale development, and livelihood pressures that encourage farmers to shift from lower-income crops to oil palm. It also emphasizes that sustainability debates are inseparable from political-economic pressures, including international market scrutiny and claims that environmental campaigns sometimes generalize beyond observed field realities. Post-2020 scholarship reinforces that “what is sustainable” cannot be evaluated solely at plot scale because the impacts of conversion depend strongly on baseline land cover (intact peat swamp forest vs logged forest vs degraded shrubland) and on the timing and intensity of drainage [10], [11], [12], [13], [14].

A cross-cutting finding is that expansion pathways matter: it has argued that not all peat oil palm development originates in peat swamp forests (including primary forests), and that some development occurs on already-modified lands such as shrublands, agroforestry, or other forms of agriculture. At the same time, multi-gas assessments of peat forest conversion to oil palm show that conversion from peat swamp forest can produce significant combined warming impacts, especially when CO₂ and N₂O are jointly considered and when early conversion phases are included. The literature, therefore, tends to converge on a conditional statement: sustainability outcomes deteriorate sharply when conversion involves clearing and draining peat swamp forests, whereas the debate shifts to the degree and management options when the baseline is already degraded peat [15], [16], [17], [18].

2. Theme 2 – Hydrology Governance is the Main “Lever.”

The groundwater level (MAT/GWL) is repeatedly treated as the pivotal variable linking drainage to peat oxidation, subsidence, and fire susceptibility, suggesting that sustainability in peat oil palm is primarily a water-governance problem. The same hydrology emphasis appears in post-2020 restoration-oriented research that evaluates canal blocking and rewetting as interventions that raise water tables and reduce peat decomposition. This alignment suggests a strong thematic convergence: although stakeholders argue about magnitudes and attribution, the core causal chain (drainage → lower water table → drier peat → higher decomposition and fire risk) is widely recognized, even if quantified differently [19], [20], [21], [22].

Evidence since 2020 has increasingly quantified outcomes of rewetting interventions. A West Kalimantan field study associated with canal-blocking rewetting projects reports that rewetting reduced peat CO₂ emissions and reduced heterotrophic respiration relative to drained oil palm sites, with mitigation effects linked to higher water tables and soil moisture. A Scientific Reports paper further argues that tropical peatland rewetting provides measurable benefits for subsidence reduction and related risk management, strengthening the case that hydrology interventions can yield both climate and long-run land-viability gains. These findings support an interpretive synthesis in which “sustainable management,” where possible, is framed less as eliminating drainage (often unrealistic for existing plantations) and more as minimizing the damaging intensity of drainage and stabilizing water regimes [3], [23], [24].

Hydrology governance also includes monitoring and spatial coordination challenges. It has been noted that sustainability concerns are linked to managed water-table depth and peat moisture above the water table, suggesting that outcomes depend on continuous control rather than a one-time infrastructure installation. Recent work on hydrological function in rewetted peatlands (including oil palm land uses) suggests that site hydrological properties can differ across land uses and may affect how rewetting changes infiltration and water movement, reinforcing that interventions are not “one-size-fits-all.” [25], [26], [27]

3. Theme 3 – GHG Emissions: Strong Signals, Contested Magnitudes, and Accounting Choices

A major point of contention is that some widely cited emission estimates may be biased upward if subsidence-based methods do not adequately separate peat oxidation from compaction/consolidation processes, and if studies do not consistently treat plant-related respiration and carbon uptake. This critique is consistent with the broader methodological point found in post-2020 peer-reviewed work: net climate impact depends on system boundaries (CO₂-only vs CO₂+CH₄+N₂O) and on whether analyses include the conversion phase. A Nature Communications study highlights that converting peat swamp forests to oil palm yields substantial combined GHG emissions, with N₂O contributing meaningfully to the total warming impact in addition to CO₂ [28], [29], [30].

Another recurring finding is time dependence. A Global Change Biology paper on peat swamp forest conversion indicates that carbon emissions can remain substantial over both short and long time frames after conversion, implying that “mature plantation” snapshots may underrepresent the conversion-driven climate burden if the early years are excluded. This time-dependence intersects with the emphasis on contested claims, because actors may selectively foreground particular stages (e.g., mature plantation management). In contrast, critics foreground land conversion and the establishment of drainage systems [31], [32], [33].

The synthesis also points to emerging attention to infrastructure-related emissions and overlooked sources. A Scientific Reports study on GHG emissions from drainage ditches in oil palm plantations (Malaysia, but relevant for similar peat drainage architectures) indicates that ditches can be distinct emission

sources, implying that plantation-scale accounting that only considers “soil surface” may miss parts of the system. This matters for sustainability practice because water governance decisions (ditch design, water levels, maintenance) are simultaneously production practices and emission-governance practices [9], [34], [35].

4. Theme 4 – Fire Risk: Dryness, Governance, and Multi-Actor Coordination

Peat fires are treated as a globally visible sustainability risk linked to peat drying and seasonal drought, and it has been also argued that unmanaged or “abandoned” peatlands can be highly fire-prone. This framing resonates with recent peat fire scholarship that analyzes fire frequency, intensity, and burn severity in peatland landscapes, strengthening the view that fire is a landscape-scale phenomenon shaped by land cover, hydrology, and human use rather than by any single commodity alone. The convergence here is that both biophysical and governance variables matter: peat moisture and water tables influence ignition and smoldering potential, while institutions influence whether land clearing uses fire and whether early suppression is feasible [36], [37], [38].

Post-2020 work provides detailed governance insights into how communities and multi-level institutions collaborate (or fail to collaborate) for fire adaptation. A study in *Ecology and Society* argues that collaborative governance for peatland fire adaptation depends on institutional arrangements, learning processes, and resource sharing, and it documents routine practices such as canal block construction, patrols, and fire response that reduce local vulnerability when cooperation is meaningful. A CIFOR-associated peer-reviewed study in *Environmental Development* reports on participatory action research approaches for community-based fire prevention and peatland restoration in Riau, linking fire-free land preparation to livelihood-oriented interventions and local institutional rules. Together, these studies support a thematic conclusion that fire prevention in peat oil palm landscapes is inseparable from livelihood systems and local incentives, not merely a technical hydrology problem [39], [40], [41], [42].

5. Theme 5 – Subsidence and Long-Run Viability As “Slow Disasters.”

This study treats subsidence as a key sustainability issue and highlights that subsidence is often incorrectly interpreted as purely decomposition-driven. At the same time, compaction and consolidation can contribute, affecting how subsidence is used as an emissions proxy. Recent peer-reviewed evidence emphasizes that rewetting can reduce subsidence, positioning subsidence not only as a geotechnical problem but also as part of climate and land-risk governance. This supports a synthesis in which subsidence becomes a long-horizon sustainability constraint: even if short-term production is feasible, the physical lowering of land surfaces can raise longer-run flood vulnerability and maintenance burdens, which in turn reshape what “sustainability” means over decades [43], [44], [45], [46].

A crucial interpretive point is that subsidence connects environmental outcomes to economic risk. Where subsidence threatens infrastructure, water control structures, and land usability, sustainability transitions must account for adaptation costs and who bears them (companies, smallholders, or the state). This aligns with emerging scholarship that frames peat restoration and water

management partly in economic terms and through risk management, indicating that restoration policies are often evaluated through feasibility, cost, and co-benefit lenses rather than climate metrics alone [47], [48], [49], [50].

6. Theme 6 – Rewetting/Restoration: Mitigation Potential Plus Social Feasibility Constraints

It has been proposed that a future direction that emphasizes intensification on existing cultivated peat, revitalization of already-developed but underused areas, and improved governance/technology (including monitoring and “digitalization”) rather than continued expansion. Post-2020 empirical work strengthens the case for mitigating rewetting in certain contexts, including field evidence that canal blocking can raise water tables and reduce CO₂ emissions relative to drained conditions, with limited change in methane uptake reported in the cited West Kalimantan study. A complementary strand of post-2020 work focuses on how to design peat restoration as a risk-managed, multi-actor process, emphasizing practical constraints, trade-offs, and uncertainty rather than assuming restoration is straightforward [25], [51], [52], [53], [54].

However, multiple sources also suggest that social acceptance and livelihood impacts shape feasibility. A peer-reviewed study on community perceptions of peat rewetting describes canal blocking, canal backfilling, and other approaches as key methods of rewetting in Indonesia, while emphasizing that rewetting is linked to national goals of reducing fires and emissions, suggesting that community perceptions are a critical factor for success. Research on rewetting in smallholder oil palm areas in Sumatra highlights livelihood implications and the need for community-aligned approaches when implementing rewetting interventions. These findings converge with the argument that sustainability advocacy must be connected to holistic development planning rather than isolated environmental mandates [4], [55], [56], [57].

7. Theme 7 – Standards and Regulation: Necessary But Not Sufficient

There is a detailed governance narrative on Indonesian sustainability standards and regulations (including ISPO and links to broader legal compliance, environmental management, and social responsibility), and it argues that claims of “no governance” are inaccurate, even if implementation is uneven. This governance framing aligns with broader scholarship that treats peat restoration and peat fire management as multi-level governance challenges in which formal rules must be matched by field capacity, monitoring, and incentives. The thematic synthesis suggests that standards can serve as a coordination device (defining expected practices such as environmental management and transparency) but cannot substitute for hydrological coordination at the peat hydrological unit scale, especially where canals connect multiple landholders [36], [58], [59].

A related post-2020 finding is that multi-actor collaboration can be undermined when power asymmetries discourage meaningful cooperation, which matters because peat hydrology interventions often require coordination beyond a single farm or company boundary. Where collaboration is weak, canal blocking or fire prevention can become fragmented, reducing effectiveness and

potentially shifting risk across boundaries. This supports a cautious policy interpretation: strengthening standards is helpful, but “sustainability on peat” requires governance that matches the landscape hydrology and resolves incentive conflicts among actors [36], [60], [61], [62].

8. Theme 8 – Future Pathways: “Better-Than-Status-Quo” Transitions

Across sources, the most feasible near-term pathway is typically framed as improving outcomes in already established peat oil palm landscapes rather than expanding into new peat areas. It has been explicitly argued for intensification, improved water management, stabilization of peat conditions, and revitalization of developed areas, consistent with post-2020 climate evidence that highlights the high emissions associated with peat conversion and the long-term persistence of carbon losses after conversion. In parallel, rewetting is positioned as a natural climate solution with potentially significant mitigation benefits in specific Indonesian contexts. Still, it is also framed as requiring risk management, institutional capacity, and livelihood-aware implementation [3], [63], [64], [65].

DISCUSSION

1 What Appears Robust Across the Evidence Base

First, the synthesis supports a robust mechanism-level conclusion: peatland hydrology is central, and the lowering of water tables through drainage is consistently linked to degradation risk pathways, even when studies differ on magnitude. Second, high-quality post-2020 multi-gas studies show that peat swamp forest conversion to oil palm can generate substantial combined warming impacts, particularly when the conversion phase and N₂O are included. Third, rewetting interventions (notably canal blocking) are repeatedly presented as a plausible mitigation option for existing drained peatlands, with field evidence indicating CO₂ reductions under rewetted conditions in at least some oil palm peatlands [3], [66], [67], [68].

2. Where Disagreement Persists (and why)

Disagreement persists partly because accounting choices change conclusions. It has been emphasized the potential overestimation when subsidence is treated as a direct emissions proxy without adequate separation of peat oxidation from compaction/consolidation, while post-2020 research emphasizes that including multiple gases and conversion phases tends to increase estimated climate impacts. A second source of disagreement concerns baselines: claims about whether oil palm expansion “causes deforestation” can look different depending on whether the baseline is primary peat swamp forest, logged forest, or already-degraded peat, which is highlighted in narrative form and post-2020 studies address through explicit land-cover accounting [30], [69], [70].

3. A Synthesis Claim That Answers the Article’s Core Question

Taken together, the evidence supports a “risk-governed trade-off” interpretation: in already converted peat landscapes, sustainability hinges on how hydrology is governed (water-table stabilization, canal design and maintenance, and fire prevention coordination), while the largest climate risks arise when new conversion and deep drainage expand into peat swamp forests.

This framing also explains why standards alone cannot solve peat sustainability challenges unless they translate into hydrological coordination at the relevant landscape scale. The next section develops this synthesis into actionable recommendations and a full conclusion aligned to your outline [48], [66], [71], [72].

4. An Integrative Causal Model: Why Water Governance Sits at the Center

The thematic synthesis supports an integrative model in which drainage intensity and the stability of groundwater levels mediate multiple sustainability outcomes simultaneously: (1) peat oxidation and CO₂ emissions, (2) peat dryness and fire vulnerability, and (3) subsidence and long-term land viability. This model is consistent with the repeated linkage of MAT/GWL to subsidence, fire risk, and GHG emissions, which implies that sustainability cannot be evaluated credibly without hydrological metrics and monitoring. It also aligns with post 2020/2024 evidence that rewetting (commonly operationalized through canal blocking) can reduce CO₂ emissions and can generate measurable benefits for slowing subsidence under certain conditions [71], [73], [74], [75].

At the same time, this model clarifies why “single-indicator” sustainability claims often produce conflict. For example, focusing solely on annual CO₂ flux can understate conversion-phase impacts and exclude N₂O, while focusing only on land-cover change can ignore management differences on already-converted peat. A multi-criteria framing—climate (multi-gas), fire, subsidence, biodiversity/land cover, and livelihoods—reduces the risk of drawing strong conclusions from partial system boundaries [1], [76], [77], [78].

5. Reconciling Contested Claims: Why Results Differ Across Studies

A key point is that emission estimates can be “too high” when subsidence is interpreted without adequately accounting for compaction and consolidation, and when measurement designs do not carefully separate root respiration, heterotrophic decomposition, and canopy uptake. That critique can be reconciled with high-impact post 2020 findings by recognizing that two different questions are often conflated: (a) “What are ongoing emissions from an established plantation under a given water regime?” versus (b) “What is the total climate cost of converting peat forest to oil palm, including the conversion phase and multiple gases?” Nature Communications evidence indicates that conversion-stage and multi-gas accounting can yield large combined warming impacts after peat swamp forest conversion, including meaningful N₂O contributions that can remain invisible in CO₂-only or post-conversion-only framings [2], [79], [80].

The time horizon and baseline condition also explain the divergence. Global Change Biology results emphasize that carbon emissions can remain substantial over both short and long time frames after conversion from logged peat swamp forest, which implies that “mature plantation snapshots” cannot be generalized into a complete life-cycle assessment. It has been argued that some peat oil palm development occurs on already-modified lands (not necessarily primary peat swamp forest) remains essential, because the baseline land cover changes the counterfactual and thus the interpretation of “additional” carbon loss and biodiversity impact [2], [81].

A further reconciliation point is infrastructure and landscape heterogeneity. Evidence that drainage ditches can be distinct GHG sources suggests that even within “the same plantation,” emissions are spatially patterned across soil surfaces, canals/ditches, and management zones, so plot-level measurements can differ depending on where sampling occurs. This supports the practical conclusion that monitoring must be designed to represent both management units and key emission “hotspots,” not just average field surfaces [9], [82].

6. Governance Implications: Standards, Regulation, and “Fit” to Peat Hydrology

It has been described that ISPO/RSPO and Indonesian legal frameworks as existing governance architectures intended to deliver legal compliance, environmental management, and social responsibility, while acknowledging that implementation is uneven (especially among smallholders). The synthesis suggests that these instruments are necessary but not sufficient for peat sustainability because peat hydrology is not confined to administrative or concession boundaries, so compliance at one site may still be undermined by upstream/downstream drainage behavior. This “scale mismatch” is a practical reason why peat sustainability often requires coordination at the peat hydrological unit level, along with shared monitoring and conflict-resolution arrangements [83], [84], [85].

Recent restoration scholarship strengthens this governance argument by emphasizing risk management, stakeholder analysis, and feasible restoration design rather than assuming linear implementation. Work on equitable and resilient peatland restoration principles in Central Kalimantan reinforces that restoration success depends on fairness, local participation, and resilience-building—factors that directly affect whether rewetting interventions persist over time. These [86]align with the warning that sustainability advocacy should connect to holistic development planning, implying that governance must integrate livelihoods and incentives rather than relying on enforcement alone [86], [87], [88], [89], [90].

7. Livelihood Implications: Why “Rewet” Must Come With Viable Economic Options

A consistent cross-source message is that rewetting is often the key technical step to reduce oxidation and fire risk, but social feasibility depends on whether land users can maintain acceptable livelihoods under wetter conditions. Research on rewetting in smallholder oil palm areas shows that rewetting interventions intersect with farmer perceptions, land-use options, and livelihood security, meaning that hydrological restoration can face resistance if it threatens income. This is consistent with “3R” restoration logics commonly used in Indonesia (rewetting, revegetation, revitalization of livelihoods), even when the technical emphasis is strongest on rewetting [91], [92], [93].

For oil palm landscapes specifically, the future pathway—emphasizing intensification on existing areas, revitalization of already developed lands, and improved water management—can be interpreted as a livelihood-compatible mitigation strategy because it aims to reduce pressure for new conversion while improving sustainability performance in current production zones. In climate-

accounting terms, this pathway also aligns with post-2020 evidence that conversion creates large climate burdens, so avoiding new conversion is often the highest-impact mitigation step [1], [94], [95], [96].

8. Monitoring and MRV: Moving From “Claims” to Auditable Sustainability

Because debates persist partly due to measurement limitations, monitoring, reporting, and verification (MRV) is central to credible peat sustainability. Post-2020 research increasingly explores remote sensing and satellite-based approaches to estimate water-table dynamics and monitor peat condition, addressing the scarcity of long-term, spatially extensive in situ groundwater observations. A 2024 review on remote sensing-based peatland monitoring highlights growing capability to track vegetation state, restoration impacts, and water table dynamics, while also noting that many studies still focus on limited areas rather than landscape-scale monitoring [97], [98], [99].

This monitoring shift aligns with the emphasis on “digitalization” and faster field problem-solving in peat oil palm management, which can be operationalized through sensor networks, groundwater monitoring stations, standardized reporting, and the integration of remote sensing with field audits. The synthesis implication is practical: better MRV can reduce narrative conflict by clarifying where peat oil palm is improving (e.g., stabilized water tables, reduced fire events) and where it is not, enabling targeted governance rather than generalized claims [54], [100], [101].

Research Gaps and Agenda

1. Multi-Gas Trade-Offs Under Realistic Management

High-impact evidence shows that multi-gas accounting can change conclusions, as N₂O can materially contribute to warming impacts after peat conversion. More field research is needed to evaluate how rewetting and water-table targets shift CO₂-CH₄-N₂O trade-offs under real plantation operations, including fertilizer regimes, drainage heterogeneity, and seasonal variability [3].

2. Attribution and Baselines in Contested Landscapes

It has been emphasized that some peat oil palm development occurs on already altered lands, suggesting that sustainability narratives must distinguish between conversion pathways and baselines. Future research should integrate land-cover history, peat depth/condition, and actor type (company vs smallholder) into comparable causal designs so that claims about “deforestation” and “emission responsibility” are not generalized across fundamentally different contexts [2].

3. Infrastructure Emissions and “Hidden” Sources

Ditch and canal emissions research indicates that drainage infrastructure can be a distinct GHG source category, suggesting the need for sampling designs and accounting frameworks that include both field surfaces and water-management infrastructure. This also implies that engineering choices (ditch depth, spacing, flow control, maintenance) may serve as mitigation levers and therefore warrant more explicit study [9].

4. Governance Effectiveness at Peat-Hydrological-Unit Scale

Evidence on collaborative adaptation for peat fires shows that multi-actor coordination, everyday practices, and institutional learning shape outcomes. Research should focus more on how hydrological-unit governance can be implemented in practice—who coordinates, who pays, how compliance is verified, and how conflicts are resolved—particularly in mixed company–smallholder landscapes [6].

5. MRV innovation and scalability

Satellite-based water-table estimation approaches demonstrate feasibility for tracking water-table dynamics where direct measurement is limited, but uncertainty and site heterogeneity remain challenges. Future work should combine remote sensing, in situ hydrology, and socio-institutional data to build auditable sustainability indicators aligned with both national policy needs and certification verification [97].

CONCLUSIONS AND RECOMMENDATIONS

This qualitative literature review with post-2020 peer-reviewed evidence—finds that peat oil palm sustainability is best understood as a risk-governed, multi-criteria challenge rather than a binary label. Hydrological governance (water-table stabilization, drainage management, and feasible rewetting) is the most consistently identified leverage point because it simultaneously affects emissions, fire vulnerability, and subsidence trajectories. The most substantial climate risks arise when new conversion and drainage expand into peat swamp forests. In contrast, the most feasible improvement pathway in already-developed peat landscapes emphasizes intensifying existing areas, improving water governance, and designing livelihood-compatible restoration plans.

Oil palm development on tropical peatlands in Indonesia has become a focal point for global sustainability debates because it concentrates climate, biodiversity, fire, and livelihood concerns in a single, highly sensitive landscape. The qualitative synthesis in this article shows that these debates cannot be reduced to simple “for or against oil palm on peat” positions, because outcomes are strongly mediated by hydrological management, baseline land cover, time horizon, and governance capacity.

Across a diverse evidence base, one conclusion stands out as particularly robust: water-table and drainage governance sit at the core of peatland sustainability in oil palm landscapes. Lowered groundwater levels are consistently associated with higher peat oxidation, greater fire vulnerability, and faster subsidence, whereas rewetting and water-table stabilization can substantially reduce CO₂ emissions and slow land degradation in at least some field contexts. This means that sustainability is not only a question of where oil palm is grown, but also of how hydrology is actively governed through canal design, operation, maintenance, and monitoring across peat hydrological units. At the same time, the review confirms that the most significant and most irreversible climate and ecological impacts arise when peat swamp forests are first converted and drained for plantations, mainly when multi-gas (CO₂, CH₄, and N₂O) and conversion-phase emissions are adequately accounted for. From a

mitigation perspective, this strengthens the case for strict protection of remaining peat swamp forests, while shifting the primary sustainability challenge in already-converted areas toward improving management, avoiding further drainage expansion, and designing feasible rewetting or partial rewetting strategies. In this sense, “sustainable oil palm on peat” is best understood as a managed-risk scenario in constrained landscapes, rather than as a fully impact-free option.

The evidence also highlights that technical feasibility alone is insufficient; social acceptance, equity, and livelihood security are critical determinants of whether restoration and water-management reforms will endure. Community-based fire prevention initiatives, participatory restoration projects, and smallholder-focused interventions demonstrate that hydrological solutions must be embedded in local economic realities and governance arrangements to be sustained over time. This underscores that peatland sustainability is not only a biophysical challenge but also a governance and justice issue, demanding attention to who bears the costs and who captures the benefits of hydrological and land-use transitions.

Finally, the review reveals significant knowledge and monitoring gaps that complicate both science and policy, including limited multi-gas field datasets under realistic management, under-representation of drainage infrastructure in GHG accounting, and incomplete MRV systems for water-table dynamics at the landscape scale. Yet emerging work on remote sensing of peat water tables, principles for equitable and resilient restoration, and risk-based restoration planning suggests that a more evidence-based and socially attuned governance of peat oil palm landscapes is possible. Advancing this agenda will require integrating hydrological science, social science, and policy design into a coherent framework that treats peatlands as coupled social-ecological systems, with oil palm management, restoration efforts, and community livelihoods co-evolving under explicit risk-governance objectives.

Recommendations (Actionable, Aligned to the Outline)

For policymakers and regulators

- Prioritize “no new conversion” safeguards for peat swamp forest and high-risk peat areas, because conversion-phase and multi-gas evidence indicate significant warming impacts after peat forest conversion to oil palm.
- Implement hydrological-unit coordination mechanisms (shared targets, shared monitoring, and dispute resolution), because peat water flows and fire risk are landscape-scale phenomena that exceed administrative boundaries.
- Treat restoration as risk management with equity safeguards, drawing on recent restoration scholarship emphasizing feasible implementation and local participation.

For Companies (Estates and Supply-Chain Actors)

- Make water management auditable by integrating water-table monitoring, maintenance logs, and remote-sensing checks, consistent with the emphasis on MAT/GWL as a key parameter and digitalization as an enabling strategy.
- Expand GHG accounting beyond “average soil surface” where feasible to include drainage infrastructure hotspots, because evidence shows ditches can be notable emission sources.
- Align sustainability reporting to multi-criteria outcomes (fire risk reduction, water-table stability, subsidence trends, and social safeguards) rather than relying on single indicators.

For Smallholders and Supporting Institutions

- Pair rewetting and fire-prevention measures with livelihood support, since evidence and restoration principles emphasize that rewetting success depends on viable economic options and perceived fairness.
- Strengthen extension and capacity building on good agricultural practices and water governance in peat contexts, because the highlights management quality as a core determinant of outcomes.

For Researchers

- Design studies that explicitly separate baseline condition, conversion phase, and mature management phase, because post-2020 evidence shows outcomes are time-dependent and system-boundary dependent.
- Build MRV methods that integrate satellite-based water-table estimation with field validation, supporting scalable monitoring where direct measurement networks are sparse.

FURTHER STUDY

This research still has limitations so that further research is needed on the topic of Peatlands, Oil Palm, and Sustainability in Indonesia: A Review of Hydrological Governance, Environmental Trade-offs, and Socioeconomic Futures to perfect this research and increase insight for readers and authors.

REFERENCES

- A. D. Ziegler et al., “Carbon outcomes of major land-cover transitions in Southeast Asia: great uncertainties and REDD+ policy implications,” *Glob. Chang. Biol.*, vol. 18, no. 10, pp. 3087–3099, Oct. 2012, doi: 10.1111/j.1365-2486.2012.02747.x.
- A. Fleming et al., “Community perceptions of peat rewetting in Tumbang Nusa Village, Indonesia,” *Mires Peat*, p. 01, 2024, doi: 10.19189/MAP.2023.OMB.SC.1983421.
- A. H. Awang et al., “Peat Land Oil Palm Farmers’ Direct and Indirect Benefits from Good Agriculture Practices,” *Sustainability*, vol. 13, no. 14, p. 7843, Jul. 2021, doi: 10.3390/su13147843.
- A. Hasanah and M. F. Setiawan, “Rewetting Design for Tropical Peatland Restoration,” *Sociae Polites*, vol. 21, no. 2, pp. 111–125, Dec. 2020, doi: 10.33541/sp.v21i3.2245.

- A. Hooijer et al., "Benefits of tropical peatland rewetting for subsidence reduction and forest regrowth: results from a large-scale restoration trial," *Sci. Rep.*, vol. 14, no. 1, p. 10721, May 2024, doi: 10.1038/s41598-024-60462-3.
- A. Noviyanto et al., "Advancing Concession-Scale Carbon Stock Prediction in Oil Palm Using Machine Learning and Multi-Sensor Satellite Indices," *Resources*, vol. 15, no. 1, p. 12, Jan. 2026, doi: 10.3390/resources15010012.
- A. Schmidt et al., "Fire frequency, intensity, and burn severity in Kalimantan's threatened Peatland areas over two Decades," *Front. For. Glob. Chang.*, vol. 7, Feb. 2024, doi: 10.3389/ffgc.2024.1221797.
- A. Triyanti, M. Indrawan, L. Nurhidayah, and M. A. Marfai, Eds., *Environmental Governance in Indonesia*, vol. 61. in *Environment & Policy*, vol. 61. Cham: Springer International Publishing, 2023. doi: 10.1007/978-3-031-15904-6.
- A. Y. A. Abdelmajeed and R. Juszczak, "Challenges and Limitations of Remote Sensing Applications in Northern Peatlands: Present and Future Prospects," *Remote Sens.*, vol. 16, no. 3, p. 591, Feb. 2024, doi: 10.3390/rs16030591.
- A. Y. Abdurrahim, "Political Ecology of Peat Landscape Dynamics in Indonesia: Access, Values, and Collective Action," IPB: Bogor Agricultural University, 2024. [Online]. Available: https://www.researchgate.net/publication/393309708_Political_Ecology_of_Peat_Landscape_Dynamics_in_Indonesia_Access_Values_and_Collective_Action_Summary
- Aidenvironment, "End Evaluation of Solidaridad's Advocacy for Change programme 2016-2020 Volume II Case studies," 2020. [Online]. Available: <https://www.government.nl/binaries/government/documenten/reports/2020/12/31/end-evaluation-of-solidaridads-advocacy-for-change-programme-2016-2020/Aidenvironment-AfP-Evaluation-Volume-II-case-studies.pdf>
- B. Hiller and J. Fisher, "A Multifunctional 'Scape Approach for Sustainable Management of Intact Ecosystems – A Review of Tropical Peatlands," *Sustainability*, vol. 15, no. 3, p. 2484, Jan. 2023, doi: 10.3390/su15032484.
- B. Schlamadinger, L. Ciccarese, M. Dutschke, P. Fearnside, S. Brown, and D. Murdiyarso, "Should We Include Avoidance of Deforestation in the International Response to Climate Change?," in *Proceedings of Workshop on Carbon Sequestration and Sustainable Livelihoods*, 1st ed., Center for International Forestry Research (CIFOR), 2005, ch. 3. doi: <https://doi.org/10.13140/2.1.2449.6967>.
- C. Henning, M. Kassie, and R. Ly, Eds., *2025 Annual Trends and Outlook Report (ATOR): Moving the Technology Frontiers in African Agrifood Systems*. AKADEMIYA2063 and International Food Policy Research Institute (IFPRI), 2026. doi: 10.54067/9798991636940.
- C. N. Mulligan, M. Fukue, and R. N. Yong, Eds., *Sustainable Practices in Geoenvironmental Engineering*, 3rd ed. CRC Press Taylor & Francis Group, 2025. [Online]. Available: <https://dokumen.pub/sustainable-practices-in-geoenvironmental-engineering-3nbsped-1032525940-9781032525945.html>

- C. S. Deshmukh et al., "Conservation slows down emission increase from a tropical peatland in Indonesia," *Nat. Geosci.*, vol. 14, no. 7, pp. 484–490, Jul. 2021, doi: 10.1038/s41561-021-00785-2.
- C. Ward et al., "Smallholder perceptions of land restoration activities: rewetting tropical peatland oil palm areas in Sumatra, Indonesia," *Reg. Environ. Chang.*, vol. 21, no. 1, p. 1, Mar. 2021, doi: 10.1007/s10113-020-01737-z.
- C. Ward et al., "Smallholder perceptions of land restoration activities: rewetting tropical peatland oil palm areas in Sumatra, Indonesia," *Reg. Environ. Chang.*, vol. 21, pp. 1–17, 2021, doi: 10.1007/s10113-020-01670-z.
- D. A. Sari et al., "Evaluating policy coherence: A case study of peatland forests on the Kampar Peninsula landscape, Indonesia," *Land use policy*, vol. 105, p. 105396, 2021, doi: <https://doi.org/10.1016/j.landusepol.2021.105396>.
- D. Galafassi, T. M. Daw, L. Munyi, K. Brown, C. Barnaud, and I. Fazey, "Learning about social-ecological trade-offs," *Ecol. Soc.*, vol. 22, no. 1, p. art2, 2017, doi: 10.5751/ES-08920-220102.
- D. J. Murphy, K. Goggin, and R. R. M. Paterson, "Oil palm in the 2020s and beyond: challenges and solutions," *CABI Agric. Biosci.*, vol. 2, no. 1, p. 39, Oct. 2021, doi: 10.1186/s43170-021-00058-3.
- D. L. A. Gaveau et al., "Slowing deforestation in Indonesia follows declining oil palm expansion and lower oil prices," *PLoS One*, vol. 17, no. 3, p. e0266178, Mar. 2022, doi: 10.1371/journal.pone.0266178.
- D. Puspitaloka, Y. Kim, H. Purnomo, and P. Z. Fulé, "Defining ecological restoration of peatlands in Central Kalimantan, Indonesia," *Restor. Ecol.*, vol. 28, no. 2, pp. 435–446, Mar. 2020, doi: 10.1111/rec.13097.
- D. Puspitaloka, Y.-S. Kim, H. Purnomo, and P. Z. Fulé, "Analysis of challenges, costs, and governance alternative for peatland restoration in Central Kalimantan, Indonesia," *Trees, For. People*, vol. 6, p. 100131, 2021, doi: <https://doi.org/10.1016/j.tfp.2021.100131>.
- D. S. Mendham et al., "Facilitating new livelihoods to promote peatland restoration in Indonesia - what are the challenges for ensuring sustainable and equitable livelihood transitions?," *Mires Peat*, vol. 30, no. 4, pp. 1–14, 2024, doi: 10.19189/MAP.2023.OMB.SC.2105613.
- E. I. K. Putri et al., "The Oil Palm Governance: Challenges of Sustainability Policy in Indonesia," *Sustainability*, vol. 14, no. 3, p. 1820, Feb. 2022, doi: 10.3390/su14031820.
- E. Saputra, "Beyond Fires and Deforestation: Tackling Land Subsidence in Peatland Areas, a Case Study from Riau, Indonesia," *Land*, vol. 8, no. 5, p. 76, Apr. 2019, doi: 10.3390/land8050076.
- F. Jaramillo et al., "The Potential of Hydrogeodesy to Address Water-Related and Sustainability Challenges," *Water Resour. Res.*, vol. 60, no. 11, Nov. 2024, doi: 10.1029/2023WR037020.
- G. C. Schoneveld, D. Ekowati, A. Andrianto, and S. Van Der Haar, "Modeling peat- and forestland conversion by oil palm smallholders in Indonesian Borneo," *Environ. Res. Lett.*, vol. 14, no. 1, 2019, doi: 10.1088/1748-9326/aaf044.

- G. Ghazaryan, L. Krupp, S. Seyfried, N. Landgraf, and C. Nendel, "Enhancing peatland monitoring through multisource remote sensing: optical and radar data applications," *Int. J. Remote Sens.*, vol. 45, no. 18, pp. 6372–6394, Sep. 2024, doi: 10.1080/01431161.2024.2387133.
- G. Z. Anshari, E. Gusmayanti, and N. Novita, "The Use of Subsidence to Estimate Carbon Loss from Deforested and Drained Tropical Peatlands in Indonesia," *Forests*, vol. 12, no. 6, p. 732, Jun. 2021, doi: 10.3390/f12060732.
- H. A. van Hardeveld, P. P. J. Driessen, P. P. Schot, and M. J. Wassen, "An integrated modelling framework to assess long-term impacts of water management strategies steering soil subsidence in peatlands," *Environ. Impact Assess. Rev.*, vol. 66, pp. 66–77, Sep. 2017, doi: 10.1016/j.eiar.2017.06.007.
- H. Purnomo et al., "Advancing palm oil sustainability to address the climate crisis: Leveraging theory of change and system dynamics model at the jurisdictional level," *For. Policy Econ.*, vol. 181, p. 103594, Dec. 2025, doi: 10.1016/j.forpol.2025.103594.
- H. Purnomo et al., *Adapting Global Palm Oil Deforestation-free Trade to Benefit Local Economies and Landscapes*. Center for International Forestry Research (CIFOR), 2022. doi: 10.17528/cifor/008636.
- H. T. L. Massop et al., "Monitoring long-term peat subsidence with subsidence platens in Zegveld, The Netherlands," *Geoderma*, vol. 450, p. 117039, Oct. 2024, doi: 10.1016/j.geoderma.2024.117039.
- H. V Cooper, C. H. Vane, S. Evers, P. Aplin, N. T. Girkin, and S. Sjögersten, "From peat swamp forest to oil palm plantations: The stability of tropical peatland carbon," *Geoderma*, vol. 342, pp. 109–117, 2019, doi: 10.1016/j.geoderma.2019.02.021.
- H. V. Cooper, S. Evers, P. Aplin, N. Crout, M. P. Bin Dahalan, and S. Sjögersten, "Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation," *Nat. Commun.*, vol. 11, no. 1, p. 407, Jan. 2020, doi: 10.1038/s41467-020-14298-w.
- I. B. G. Sutawijaya, A. Suwarno, and L. Hein, "Socio-Economic Benefits of Different Indonesian Crops: Opportunities for Sago Starch in Bioplastic Development," *Sustainability*, vol. 17, no. 16, p. 7351, Aug. 2025, doi: 10.3390/su17167351.
- I. Thushari et al., "A blueprint of initial LCA in Agri-food production systems: Practical recommendations for crop and livestock production systems," *Agric. Syst.*, vol. 234, p. 104668, Apr. 2026, doi: 10.1016/j.agry.2026.104668.
- J. B. Kauffman et al., "Protocols for the measurement, monitoring, and reporting of structure, biomass, carbon stocks and greenhouse gas emissions in tropical peat swamp forests," 2017. doi: 10.17528/cifor/006429.
- J. Cannon, "Ditches on peatland oil palm plantations are an overlooked source of methane: Study," *Mongabay Asia*. Accessed: Apr. 03, 2026. [Online]. Available: <https://news.mongabay.com/2025/12/ditches-on-peatland-oil-palm-plantations-are-an-overlooked-source-of-methane-study/>
- J. Hammerich, "Assessing the effects of peatland restoration," *Leuphana University Luneburg*, 2024. doi: <https://doi.org/10.48548/pubdata-1388>.

- J. Hammerich, C. Schulz, R. Probst, T. Lüdicke, and V. Luthardt, "Carbon content and other soil properties of near-surface peats before and after peatland restoration," *PeerJ*, vol. 12, p. e17113, Apr. 2024, doi: 10.7717/peerj.17113.
- J. J. Bogardi et al., *Handbook of Water Resources Management: Discourses, Concepts and Examples*, 1st ed. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-60147-8.
- J. McCalmont et al., "Short- and long-term carbon emissions from oil palm plantations converted from logged tropical peat swamp forest," *Glob. Chang. Biol.*, vol. 27, no. 11, pp. 2361–2376, Jun. 2021, doi: 10.1111/gcb.15544.
- J. Newig and T. Moss, "Scale in environmental governance: moving from concepts and cases to consolidation," *J. Environ. Policy Plan.*, vol. 19, no. 5, pp. 473–479, Sep. 2017, doi: 10.1080/1523908X.2017.1390926.
- J. Panggabean, J. Kurnia, and T. Shaumul, "Sea Level Rise Impacts on Coastal Oil Palm Plantations," *IJOP Int. J. Oil Palm*, vol. 8, no. 1, pp. 1–14, 2025, doi: 10.35876/ijop.v8i1.138.
- J. S. Price, C. P. R. McCarter, and W. L. Quinton, *Groundwater in Peat and Peatlands*. Guelph, Ontario: The Groundwater Project, 2023. [Online]. Available: https://www.researchgate.net/publication/372720326_Groundwater_in_Peat_and_Peatlands
- J. Sayer, J. Ghazoul, P. Nelson, and A. Klintuni Boedhihartono, "Oil palm expansion transforms tropical landscapes and livelihoods," *Glob. Food Sec.*, vol. 1, no. 2, pp. 114–119, Dec. 2012, doi: 10.1016/j.gfs.2012.10.003.
- J. T. Raharjo, R. Fauzi, F. S. Rudi, and A. W. Nugroho, "Exploring Community Perceptions of Peatland Restoration in West Kalimantan, Indonesia," *Mires Peat*, vol. 32, Aug. 2025, doi: 10.19189/001c.142922.
- K. Kasak et al., "Greenhouse gas emissions from ditches in oil palm plantations on tropical peatlands in Malaysia," *Sci. Rep.*, vol. 15, no. 1, p. 37126, Oct. 2025, doi: 10.1038/s41598-025-21094-3.
- K. Obidzinski, A. Dermawan, and A. Hadianto, "Oil palm plantation investments in Indonesia's forest frontiers: limited economic multipliers and uncertain benefits for local communities," *Environ. Dev. Sustain.*, vol. 16, no. 6, pp. 1177–1196, Dec. 2014, doi: 10.1007/s10668-014-9519-8.
- K. W. Abbott, P. Genschel, D. Snidal, and B. Zangl, "Orchestrating global governance," in *International Organizations as Orchestrators*, 1st ed., Cambridge University Press, 2015, pp. 349–379. doi: 10.1017/CBO9781139979696.018.
- L. Hein, E. Sumarga, M. Quiñones, and A. Suwarno, "Effects of soil subsidence on plantation agriculture in Indonesian peatlands," *Reg. Environ. Chang.*, vol. 22, no. 4, 2022, doi: 10.1007/s10113-022-01979-z.
- L. Hein, E. Sumarga, M. Quiñones, and A. Suwarno, "Effects of soil subsidence on plantation agriculture in Indonesian peatlands," *Reg. Environ. Chang.*, vol. 22, no. 4, p. 121, Dec. 2022, doi: 10.1007/s10113-022-01979-z.

- L. Ikkala, A.-K. Ronkanen, O. Utriainen, B. Kløve, and H. Marttila, "Peatland subsidence enhances cultivated lowland flood risk," *Soil Tillage Res.*, vol. 212, p. 105078, Aug. 2021, doi: 10.1016/j.still.2021.105078.
- L. Judijanto, "Beyond deforestation debates: a review of social issue blindspots in EU palm oil trade policies," *Rev. Caribeña Ciencias Soc.*, vol. 14, no. 8, p. e4750, Aug. 2025, doi: 10.55905/rcssv14n8-015.
- L. Judijanto, "Significant Contributions of Oil Palm Plantation towards Sustainable Development Goals in Rural Livelihood," *ARACÊ*, vol. 7, no. 6, pp. 34217-34239, Jun. 2025, doi: 10.56238/arev7n6-299.
- L. Judijanto, "Treasure from Palm Oil Waste: POME as Low-Emission Fuel for Aviation," *J. Sci. Eng. Adv.*, vol. 1, no. 2, pp. 1-11, Oct. 2025, doi: 10.63721/25JSEA0104.
- L. Potter, "Managing oil palm landscapes: a seven-country survey of the modern palm oil industry in Southeast Asia, Latin America and West Africa," 2015. [Online]. Available: <https://pdfs.semanticscholar.org/5320/40a48115a799216ee9507943fdd3fcef1b23.pdf>
- M. A. Imron, F. D. Rachmawati, T. Dewi, D. Albiyah, G. M. I. Simanullang, and E. E. Poor, "Effect of canal blocking on biodiversity of degraded peatlands: Insight from West Kalimantan," *PLoS One*, vol. 20, no. 10, p. e0334014, Oct. 2025, doi: 10.1371/journal.pone.0334014.
- M. A. Miller, "Market-based commons: Social agroforestry, fire mitigation strategies, and green supply chains in Indonesia's peatlands," *Trans. Inst. Br. Geogr.*, vol. 47, no. 1, pp. 77-91, Mar. 2022, doi: 10.1111/tran.12472.
- M. Ali, Ed., *The Functioning of Ecosystems*. IntechOpen, 2012. [Online]. Available: <https://courseware.cutm.ac.in/wp-content/uploads/2020/06/Functions-of-ecosystem.pdf>
- M. Fischer et al., "Rethinking Land in the Anthropocene: from Separation to Integration," 2021. [Online]. Available: https://epic.awi.de/id/eprint/59548/1/WBGU_HGL2020_en.pdf
- M. Harianti, T. B. Prasetyo, J. Junaidi, G. Gusmini, and A. F. Yenad, "The Physical Property Changes of Peatland upon Conversion of Oil Palm Plantation to Corn Cropping in Kinali, West Pasaman, West Sumatera," *J. Ilmu Pertan. Indones.*, vol. 27, no. 4, pp. 502-513, Oct. 2022, doi: 10.18343/jipi.27.4.502.
- M. Huitric, *Biodiversity, Ecosystem Services and Resilience: Governance for a Future with Global Changes*, 1st ed. Stockholm: Albaeco, 2009. [Online]. Available: https://www.stockholmresilience.org/download/18.235c0ace124479a1f73800013572/1459560202956/Tjarno_report_final.pdf
- M. K. Samuel and S. L. Evers, "Assessing the potential of compaction techniques in tropical peatlands for effective carbon reduction and climate change mitigation," *SN Appl. Sci.*, vol. 5, no. 12, p. 347, Dec. 2023, doi: 10.1007/s42452-023-05548-9.

- M. Lupascu et al., "Climate-smart peatland management and the potential for synergies between food security and climate change objectives in Indonesia," *Glob. Environ. Chang.*, vol. 82, p. 102731, 2023, doi: <https://doi.org/10.1016/j.gloenvcha.2023.102731>.
- M. M. Mleczko et al., "Tropical peatland hydrological dynamics affect the efficacy of C-band Small BAseline Subset InSAR approaches," *Remote Sens. Environ.*, vol. 331, p. 115009, Dec. 2025, doi: [10.1016/j.rse.2025.115009](https://doi.org/10.1016/j.rse.2025.115009).
- M. S. Reed et al., "Transforming tropical peatland governance to manage climate risks using the Three Horizons method," *PLoS One*, vol. 20, no. 11, p. e0324399, Nov. 2025, doi: [10.1371/journal.pone.0324399](https://doi.org/10.1371/journal.pone.0324399).
- M. Siarudin et al., "Carbon Sequestration Potential of Agroforestry Systems in Degraded Landscapes in West Java, Indonesia," *Forests*, vol. 12, no. 6, p. 714, May 2021, doi: [10.3390/f12060714](https://doi.org/10.3390/f12060714).
- N. Gatis et al., "Peatland restoration increases water storage and attenuates downstream stormflow but does not guarantee an immediate reversal of long-term ecohydrological degradation," *Sci. Rep.*, vol. 13, no. 1, p. 15865, Sep. 2023, doi: [10.1038/s41598-023-40285-4](https://doi.org/10.1038/s41598-023-40285-4).
- N. H. Batjes et al., "Towards a modular, multi-ecosystem monitoring, reporting and verification (MRV) framework for soil organic carbon stock change assessment," *Carbon Manag.*, vol. 15, no. 1, Dec. 2024, doi: [10.1080/17583004.2024.2410812](https://doi.org/10.1080/17583004.2024.2410812).
- N. I. Fawzi et al., "Integrated water management practice in tropical peatland agriculture has low carbon emissions and subsidence rates," *Heliyon*, vol. 10, no. 5, p. e26661, Mar. 2024, doi: [10.1016/j.heliyon.2024.e26661](https://doi.org/10.1016/j.heliyon.2024.e26661).
- N. Koupaei-Abyazani et al., "Tropical Peatland Water Table Estimations From Space," *J. Geophys. Res. Biogeosciences*, vol. 129, no. 6, pp. 1–22, Jun. 2024, doi: [10.1029/2024JG008116](https://doi.org/10.1029/2024JG008116).
- N. Novita et al., "Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands," *Sci. Total Environ.*, vol. 952, p. 175829, Nov. 2024, doi: [10.1016/j.scitotenv.2024.175829](https://doi.org/10.1016/j.scitotenv.2024.175829).
- N. S. Lestari et al., "Opportunities and risk management of peat restoration in Indonesia: lessons learned from peat restoration actors," *Restor. Ecol.*, vol. 32, no. 1, Jan. 2024, doi: [10.1111/rec.14054](https://doi.org/10.1111/rec.14054).
- P. Ghezelayagh, A. Kamocki, P. Banaszuk, and M. Grygoruk, "Towards a remote sensing-based assessment of carbon emissions from peatlands," *Sci. Rep.*, vol. 15, no. 1, p. 34175, Oct. 2025, doi: [10.1038/s41598-025-15293-1](https://doi.org/10.1038/s41598-025-15293-1).
- R. Djalante, J. Jupesta, and E. Aldrian, *Climate Change Research, Policy and Actions in Indonesia: Science, Adaptation and Mitigation*, 1st ed. Springer Climate, 2021. [Online]. Available: <https://dokumen.pub/climate-change-research-policy-and-actions-in-indonesia-science-adaptation-and-mitigation-1st-ed-9783030555351-9783030555368.html>
- R. Gearey et al., "Policy Options in Peatland Conservation and Restoration: A Review of the UNEP Global Peatlands Assessment and Future Strategy for Global Governance," *Mires Peat*, vol. 32, p. 26, Oct. 2025, doi: [10.19189/001c.146134](https://doi.org/10.19189/001c.146134).

- R. Hazriani, S. Oktoriana, and Romiyanto, "Mapping the Potential Use of Peat Land to Formulate a Management Strategy for Smallholder Palm Oil Plantations," *J. Ilmu Pertan. Indones.*, vol. 31, no. 1, pp. 142–150, Oct. 2025, doi: 10.18343/jipi.31.1.142.
- R. M. Ochieng, "The role of forests in climate change mitigation : a discursive-institutional analysis of REDD+ MRV," Wageningen University, 2017. doi: 10.18174/412210.
- R. Purnamayani, S. D. Tarigan, S. Sudradjat, H. Syahbuddin, A. Dariah, and B. Kartiwa, "How Do Groundwater Levels and Soil Moisture Influence the Peat Fire Vulnerability Index in Oil Palm Plantations?," *J. Trop. Crop Sci.*, vol. 12, no. 01, pp. 235–245, Mar. 2025, doi: 10.29244/jtcs.12.01.235-245.
- R. Ramdani and I. Mustalahti, "Collaborative everyday adaptation to deal with peatland fires: a case study on the east coast of Sumatra, Indonesia," *Ecol. Soc.*, vol. 28, no. 3, p. art12, 2023, doi: 10.5751/ES-14263-280312.
- R. Sari, "Study: Rewetting in Oil Palm Plantations Has the Potential to Reduce Emissions," *Konservasi Alam Nusantara: Press Releases*. Accessed: Mar. 12, 2026. [Online]. Available: <https://www.ykan.or.id/en/publications/articles/press-release/oil-palm-plantations-has-the-potential-to-reduce-emissions/>
- R. Y. Mahardika et al., "Hydrological function of rewetted peatlands linked to saturated hydraulic conductivity in Kubu Raya, West Kalimantan, Indonesia," *J. Degrad. Min. Lands Manag.*, vol. 11, no. 3, pp. 5717–5725, Apr. 2024, doi: 10.15243/jdmlm.2024.113.5717.
- R. Zoboli, M. Mazzanti, and S. Tagliapietra, Eds., *Economic Policies for the Sustainability Transition*. MDPI, 2024. doi: 10.3390/books978-3-7258-1841-9.
- S. Anamulai, R. Sanusi, A. Zubaid, A. M. Lechner, A. Ashton-Butt, and B. Azhar, "Land use conversion from peat swamp forest to oil palm agriculture greatly modifies microclimate and soil conditions," *PeerJ*, vol. 7, p. e7656, Oct. 2019, doi: 10.7717/peerj.7656.
- S. Connop, C. Nash, J. Elliot, D. Haase, and D. Dushkova, "Nature-based solution evaluation indicators: Environmental Indicators Review," 2020. [Online]. Available: https://connectingnature.eu/sites/default/files/images/inline/CN_Env_Indicators_Review.pdf
- S. H. Silviana, B. H. Saharjo, S. Sutikno, E. I. Putra, and I. Basuki, "The Effect of Fire and Rewetting on the Groundwater Level in Tropical Peatlands," in *Tropical Peatland Eco-management*, M. Osaki, N. Tsuji, N. Foad, and J. Rieley, Eds., Singapore: Springer Singapore, 2021, pp. 613–624. doi: 10.1007/978-981-33-4654-3_22.
- S. Hutabarat, "Challenges on Peatland Restoration: From Oil Palm Plantation to Sustainable Peatland Ecosystem," in *Proceedings of the International Conference on Natural Resources and Sustainable Development*, SCITEPRESS - Science and Technology Publications, 2022, pp. 512–520. doi: 10.5220/0009905400002480.

- S. Mishra et al., "Degradation of Southeast Asian tropical peatlands and integrated strategies for their better management and restoration," *J. Appl. Ecol.*, vol. 58, no. 7, pp. 1370–1387, Jul. 2021, doi: 10.1111/1365-2664.13905.
- S. N. F. Azizan et al., "Comparing GHG Emissions from Drained Oil Palm and Recovering Tropical Peatland Forests in Malaysia," *Water*, vol. 13, no. 23, p. 3372, Nov. 2021, doi: 10.3390/w13233372.
- S.-M. Jalilov, Y. Rochmayanto, D. C. Hidayat, J. T. Raharjo, D. Mendham, and J. D. Langston, "Unveiling economic dimensions of peatland restoration in Indonesia: A systematic literature review," *Ecosyst. Serv.*, vol. 71, p. 101693, 2025, doi: <https://doi.org/10.1016/j.ecoser.2024.101693>.
- T. D. Toumbourou et al., "Principles for equitable and resilient tropical peatland restoration in Central Kalimantan, Indonesia," *Restor. Ecol.*, vol. 32, no. 7, Sep. 2024, doi: 10.1111/rec.14221.
- T. Darusman, D. Murdiyarso, Impron, and I. Anas, "Effect of rewetting degraded peatlands on carbon fluxes: a meta-analysis," *Mitig. Adapt. Strateg. Glob. Chang.*, vol. 28, no. 3, p. 10, Mar. 2023, doi: 10.1007/s11027-023-10046-9.
- V. Camacho-Valdez, R. Rodiles-Hernández, D. A. Navarrete-Gutiérrez, and E. Valencia-Barrera, "Tropical wetlands and land use changes: The case of oil palm in neotropical riverine floodplains," *PLoS One*, vol. 17, no. 5, p. e0266677, May 2022, doi: 10.1371/journal.pone.0266677.
- W. Sierra-Barón, O. Navarro, D. K. Amézquita Naranjo, E. D. Teres Sierra, and C. M. Narváez González, "Beliefs about Climate Change and Their Relationship with Environmental Beliefs and Sustainable Behavior: A View from Rural Communities," *Sustainability*, vol. 13, no. 9, p. 5326, May 2021, doi: 10.3390/su13095326.
- W. Xiong, J. Li, and B. Liu, "Coastal Wetland Conservation and Urban Sustainable Development Synergy Pathway Research: Insights from Qingdao and Weihai for Qinhuangdao," *Sustainability*, vol. 17, no. 21, p. 9902, Nov. 2025, doi: 10.3390/su17219902.
- Y. Dong, M. Hauschild, H. Sørup, R. Rousselet, and P. Fantke, "Evaluating the monetary values of greenhouse gases emissions in life cycle impact assessment," *J. Clean. Prod.*, vol. 209, pp. 538–549, Feb. 2019, doi: 10.1016/j.jclepro.2018.10.205.
- Y. K. Choy and A. Onuma, "The Tropical Peatlands in Indonesia and Global Environmental Change: A Multi-Dimensional System-Based Analysis and Policy Implications," *Reg. Sci. Environ. Econ.*, vol. 2, no. 3, p. 17, Jul. 2025, doi: 10.3390/rsee2030017.