



Regional Ecosystem Carrying Capacity and Sustainable Palm Oil Development: A Review on Land-Water-Carbon-Hydrological-Ecological Dimensions and Optimal Spatial Allocation

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ABSTRACT

The rapid expansion of oil palm (*Elaeis guineensis*) plantations across tropical regions, particularly Indonesia, has intensified debates over ecological thresholds and regional carrying capacity. This qualitative literature review synthesizes recent evidence (2020–2026) on ecosystem carrying capacity across five interlocking dimensions—land and water resources, carbon sequestration, hydrological regulation, ecological integrity, and disaster mitigation—within the context of sustainable palm oil development. The analysis integrates multi-commodity land-suitability assessments and evaluates optimal proportions of forest, food crops, oil palm, infrastructure, and other land uses within Indonesian spatial planning frameworks. Findings indicate that many lowland and peatland landscapes have approached or exceeded critical carrying capacity limits, with water resource constraints, carbon emissions from peat conversion, and altered hydrological regimes posing systemic risks. While legal benchmarks mandate minimum forest cover of 30% per river basin or island, empirical evidence suggests that functional hydrological regulation and biodiversity conservation often require higher set-asides and strategic riparian buffers. Multi-criteria decision analysis and GIS-based land evaluation identify significant opportunities to reallocate degraded or idle land to oil palm while protecting high-conservation-value areas. The review concludes that sustainable palm oil development must shift from area expansion to yield intensification, landscape optimization, and strict adherence to ecological thresholds

INTRODUCTION

Background

The global vegetable oil market has witnessed unprecedented growth over the past two decades, with palm oil emerging as the dominant commodity, accounting for approximately 35% of world vegetable oil consumption. Indonesia, as the world's largest producer and exporter, contributed 59% of the global palm oil supply in 2023, generating substantial foreign exchange earnings and supporting rural livelihoods for over 16 million smallholders and plantation workers. However, this economic success has precipitated profound ecological transformations across the archipelago's lowland tropics. Between 2001 and 2023, Indonesia lost 27.1 million hectares of primary and secondary forest, with oil palm expansion identified as a primary driver in Sumatra, Kalimantan, and Papua. The conversion of peat swamp forests – carbon-dense ecosystems storing up to 2,000 tonnes of carbon per hectare – has triggered large-scale greenhouse gas (GHG) emissions, biodiversity loss, and hydrological disruption [1].

Concurrently, the concept of ecosystem carrying capacity (ECC) has gained traction in regional planning and environmental policy as a framework for quantifying the maximum sustainable use of natural resources without irreversible degradation. ECC encompasses supportive capacity (resource availability) and assimilative capacity (pollution absorption), providing a scientifically grounded basis for zoning, licensing, and land-use optimization. In Indonesia, Law No. 41/1999 on Forestry mandates that each river basin or island maintain at least 30% forest cover to ensure hydrological stability and disaster mitigation. Yet empirical evidence suggests that this threshold may be insufficient in peat-dominated watersheds or regions experiencing intensified rainfall variability under climate change. The interplay between legally prescribed forest proportions, multi-commodity land demands, and ecological thresholds remains inadequately integrated into spatial planning instruments, leading to policy incoherence and on-the-ground conflicts [2].

Problem Statement and Urgency

The urgency of embedding ECC principles into palm oil governance stems from three converging crises. First, land and water resources in major palm oil provinces are approaching critical limits. In Riau, Jambi, and Central Kalimantan, available lowland areas suitable for oil palm without deforestation or peat conversion have dwindled, pushing expansion into marginal lands with high environmental risks. Second, carbon emissions from peatland drainage and plantation establishment have undermined Indonesia's climate commitments under the Paris Agreement. Despite the FOLU Net Sink 2030 target, emissions from peat oxidation and fires continue to offset gains from forest protection. Third, altered hydrological regimes – characterized by increased surface runoff, reduced baseflow, and heightened flood frequency – have compromised ecosystem services and community livelihoods. Oil palm plantations, with their uniform canopy structure and intensive drainage networks, exhibit lower evapotranspiration and infiltration rates compared to natural forests, exacerbating drought and flood cycles [3], [4].

These ecological pressures are compounded by governance challenges. Spatial planning processes often lack robust ECC assessments, relying instead on sectoral targets that prioritize agricultural expansion over environmental sustainability. The absence of integrated, multi-commodity land suitability frameworks results in suboptimal land allocation, where high-potential food crop zones are converted to oil palm, while degraded lands remain underutilized. Consequently, the proportion of forest, food crops, oil palm, infrastructure, and other uses in any given region rarely reflects ecological optima, leading to cumulative environmental degradation and social conflict [5], [6].

Objectives and Research Questions

This article aims to synthesize contemporary evidence on regional ecosystem carrying capacity and its implications for sustainable palm oil development in Indonesia. The overarching objective is to develop a conceptual framework that integrates land, water, carbon, hydrological, and ecological dimensions into spatial planning and policy. Specific research questions guiding this review are:

1. What are the current trends and thresholds in land and water carrying capacity in Indonesia's major oil palm regions?
2. How does oil palm expansion affect carbon sequestration capacity and long-term GHG emissions, particularly on peat and mineral soils?
3. What are the hydrological consequences of forest-to-oil-palm conversion, and how can these be mitigated through landscape design?
4. What multi-commodity land suitability approaches can optimize spatial allocation among forest, food crops, oil palm, and infrastructure?
5. What are the scientifically and legally grounded optimal proportions of land uses that ensure ecological integrity while supporting economic development?

By addressing these questions, the article seeks to bridge the gap between ecological science and policy practice, offering actionable recommendations for embedding ECC into Indonesia's palm oil governance framework.

Structure of the Article

The remainder of this article is organized as follows. Section 2 reviews conceptual and theoretical foundations of ECC, ecosystem services, and sustainable palm oil. Section 3 outlines the qualitative literature review methodology, including search strategy and analytical procedures. Section 4 presents thematic findings on land and water carrying capacity, carbon sequestration, hydrological functions, ecological integrity, and multi-commodity land suitability. Section 5 synthesizes these findings, discusses implications for spatial planning, and proposes design principles for ECC-based landscapes. Section 6 concludes with substantive insights and policy recommendations.

LITERATURE RIVIEW

Ecosystem Carrying Capacity in Regional Planning

Ecosystem carrying capacity is defined as the maximum level of resource use or pollutant discharge that an ecosystem can sustain without compromising its structure, function, and ability to support future generations. The concept originated in population ecology but has been adapted to regional planning to assess limits in land use, water extraction, waste assimilation, and biodiversity conservation. In Indonesia, ECC assessments have been institutionalized through Ministerial regulations requiring environmental carrying capacity analyses for spatial planning, infrastructure projects, and agricultural zoning [7].

Two dimensions of ECC are particularly relevant to palm oil development. Supportive carrying capacity refers to the availability of natural resources—land, water, nutrients—to sustain agricultural production. Assimilative carrying capacity denotes the ecosystem's ability to absorb pollutants, including GHG emissions, nutrient runoff, and sediment loads, without degradation. In oil palm landscapes, supportive capacity is constrained by soil fertility, slope, and climate, while assimilative capacity is challenged by peat oxidation, agrochemical runoff, and biodiversity loss. Recent assessments in Indonesian watersheds reveal that many regions have exceeded supportive capacity, with land scarcity forcing expansion onto peatlands and steep slopes, while assimilative capacity is overwhelmed by emissions and water pollution [8]. Indicators for ECC include resource stock indicators (e.g., available land area, water yield), environmental quality indicators (e.g., carbon stock, water quality index), and threshold indicators (e.g., minimum forest cover, riparian buffer width). However, methodological inconsistencies persist. Some studies adopt a purely biophysical approach, while others integrate socio-economic variables, leading to divergent capacity estimates. Moreover, scalar mismatches between plot-level assessments and regional planning often obscure cumulative impacts, necessitating multi-scale frameworks that link farm, watershed, and provincial scales [9].

Ecosystem Services in Oil Palm-Dominated Landscapes

Ecosystem services (ES) are the benefits humans derive from ecosystems, categorized as provisioning (food, timber), regulating (climate, water), supporting (soil formation, nutrient cycling), and cultural (recreation, spiritual). Oil palm plantations provide significant provisioning services, supplying 36% of global vegetable oil demand and supporting rural economies. However, they often compromise regulating and supporting services, particularly when established in forests or peatland [8].

Trade-offs between ES are stark. Conversion of primary forest to oil palm reduces aboveground carbon stocks by 120–200 tonnes C ha⁻¹ and eliminates habitat for endangered species such as orangutans and tigers. On peatlands, drainage for oil palm triggers continuous carbon loss of 10–20 tonnes C ha⁻¹ yr⁻¹, turning landscapes from carbon sinks to net sources. Hydrological regulation also suffers; oil palm plantations increase surface runoff by 30–50% and reduce dry-season baseflow, elevating flood and drought risks. Conversely, integrating set-asides, riparian buffers, and agroforestry can enhance ES bundles,

maintaining biodiversity and hydrological functions while sustaining oil palm yields [10].

Landscape-scale approaches, such as the High Conservation Value (HCV) and High Carbon Stock (HCS) frameworks, aim to balance production and conservation by zoning landscapes into protection, management, and development areas. The Indonesian Sustainable Palm Oil (ISPO) and Roundtable on Sustainable Palm Oil (RSPO) standards incorporate these concepts, yet implementation gaps persist, with only 15% of Indonesian plantations certified under RSPO as of 2023. Moreover, the focus on individual concessions often neglects cumulative landscape-level impacts, underscoring the need for jurisdictional approaches that align private sector actions with regional ECC limits [11].

Sustainable Palm Oil, Forest Cover Norms, and Spatial Allocation

Indonesian law mandates that each river basin or island maintain at least 30% forest cover to ensure hydrological stability, disaster mitigation, and biodiversity conservation. This benchmark, rooted in the 1999 Forestry Law, is based on early hydrological studies suggesting that 30% forest cover is the minimum required to maintain baseflow and reduce flood peaks. However, recent research indicates that the optimal forest proportion varies with topography, soil type, and climate, with peat-dominated watersheds requiring 50–70% forest cover to prevent subsidence and fire. Furthermore, the 30% threshold is often interpreted as a target rather than a minimum, leading to complacency in forest protection [12], [13], [14].

Spatial allocation among forest, food crops, oil palm, infrastructure, and other uses is further complicated by multi-commodity land suitability assessments. These evaluations use GIS-based multi-criteria decision analysis (MCDA) to match land characteristics with crop requirements, considering slope, soil depth, drainage, rainfall, and market access. Studies in Sumatra and Kalimantan reveal that 30–40% of land currently under oil palm is moderately to marginally suitable, while large tracts of degraded land with high suitability remain idle. This misallocation reflects policy biases toward plantation expansion over intensification and landscape restoration [15].

The food-forest-palm oil-infrastructure nexus is central to Indonesia's development agenda. The government aims to increase palm oil production to 60 million tonnes by 2045 while achieving food self-sufficiency and reducing deforestation. These goals are inherently conflicting without explicit ECC-based zoning. The World Bank's Sustainable Lowland Agriculture Development report highlights that optimizing land use through multi-commodity suitability analysis could meet production targets within existing agricultural lands, avoiding further forest and peat conversion. However, this requires robust governance, accurate land data, and enforcement of spatial plans – areas where Indonesia faces persistent challenges [16].

METHODOLOGY

Research Design: Qualitative, Narrative Literature Review

This study employs a qualitative, narrative literature review methodology to synthesize contemporary evidence on ecosystem carrying capacity and sustainable palm oil development. Unlike systematic reviews, which follow rigid protocols for exhaustive searches and statistical meta-analysis, qualitative reviews prioritize interpretive synthesis, conceptual development, and policy relevance. This approach is appropriate for complex, multi-dimensional topics where quantitative homogeneity is lacking and where the goal is to build theoretical frameworks rather than aggregate effect sizes [17].

The epistemological stance is constructivist-interpretive, recognizing that ECC is not a fixed biophysical constant but a socially constructed concept shaped by scientific discourse, policy priorities, and stakeholder interests. The analytical focus is thematic, examining how land, water, carbon, hydrological, and ecological dimensions interact in palm oil landscapes and how these interactions inform spatial planning. The review draws on diverse disciplines—ecology, hydrology, agronomy, geography, and environmental policy—to construct a holistic understanding [18].

Literature Search and Selection Strategy

The search strategy targeted peer-reviewed journal articles, policy reports, and technical documents published between 2020 and 2025, supplemented by seminal pre-2020 works where necessary. Databases included Scopus, Web of Science, Google Scholar, and institutional repositories (CIFOR, World Bank, FAO). Keywords encompassed “ecosystem carrying capacity,” “land suitability,” “oil palm carbon,” “hydrological impacts,” “forest cover 30%,” and “sustainable palm oil Indonesia.”

Inclusion criteria were: (1) empirical or theoretical focus on ECC dimensions in tropical landscapes; (2) relevance to the Indonesian palm oil sector; (3) publication in reputable journals or by authoritative institutions; (4) methodological transparency. Exclusion criteria included: (1) purely technical agronomic studies without spatial or ecological dimensions; (2) opinion pieces lacking empirical grounding; (3) studies focusing exclusively on non-Indonesian contexts without transferable insights.

The final corpus comprised 57 documents, including 45 peer-reviewed articles, 7 policy reports, and 5 technical guidelines. Studies were characterized by geographic scale (plot, farm, watershed, province, national), land type (peat, mineral), and governance context (smallholder, corporate, jurisdictional).

Analytical Procedures

Thematic coding was conducted using a deductive-inductive framework. Preliminary codes aligned with the five ECC dimensions (land/water, carbon, hydrology, ecology, spatial allocation). Emergent codes captured governance gaps, policy instruments, and stakeholder perspectives. Cross-case comparison identified patterns across regions (Sumatra, Kalimantan, Papua) and land-use systems (forest, oil palm, agroforestry, food crops).

Limitations include potential publication bias toward negative impacts of oil palm, disciplinary bias toward biophysical over social dimensions, and data gaps on smallholder systems and post-2023 developments. The qualitative

approach mitigates these limitations through iterative reflection and transparent acknowledgment of biases, though generalization must be cautious.

RESULT

Land and Water Carrying Capacity in Oil Palm Regions

1. Trends in Land Availability and Signs of Over-Capacity

Indonesia's oil palm area expanded from 6.5 million hectares in 2000 to 16.9 million hectares in 2023, with 85% of the area concentrated in Sumatra and Kalimantan. However, available lowland areas meeting suitability criteria without encroaching on forest or peat have largely been exhausted. In Riau Province, historically the center of oil palm development, only 1.2 million hectares of suitable degraded land remain available, yet 2.3 million hectares of marginal land (slopes >8%, low fertility) are under active consideration for conversion. This spatial mismatch signals that supportive carrying capacity in traditional palm oil zones has been reached or exceeded [3], [19], [20], [21].

Evidence of over-capacity is multifaceted. First, expansion is increasingly directed to peatlands, which occupy 14.9 million hectares (8.3% of Indonesia's land area) but account for 45% of carbon stocks. Between 2015 and 2023, an estimated 850,000 hectares of peatland were converted or degraded, predominantly for plantation agriculture. Second, productivity gaps indicate that the sector's growth has decoupled from area expansion; oil palm yields in Indonesia average 3.5 tonnes fresh fruit bunch (FFB) per hectare, 40% below the global potential of 5–6 tonnes ha⁻¹, suggesting that intensification, not expansion, is the productivity frontier. Third, land conflicts and tenure insecurity – documented in 350+ community land disputes involving oil palm concessions – reflect the social costs of expansion into marginal and customary lands [13], [15], [22], [23], [24].

Water carrying capacity faces concurrent pressures. Indonesia's lowland provinces experience high inter-annual rainfall variability (coefficient of variation >0.3), with El Niño-driven droughts and La Niña-driven floods increasing in frequency and intensity. Oil palm's water demand peaks during dry seasons, competing with food crop irrigation, urban supply, and ecosystem maintenance flows. In Jambi Province, dry-season water yield has declined by 15–25% between 2000 and 2023, coinciding with 60% forest loss and 45% oil palm expansion. A 2024 assessment of water resources carrying capacity in six Indonesian oil palm provinces concluded that three (Riau, Jambi, Central Kalimantan) have exceeded sustainable extraction limits, with projected deficits of 3–8 billion m³ yr⁻¹ by 2050 under climate change scenarios [25], [26].

2. Environmental Carrying Capacity Assessments in the Indonesian Context

Environmental carrying capacity assessments in Indonesia employ varied methodologies, yielding divergent results. The Indonesian Ministry of Environment and Forestry has developed standardized ECC frameworks for spatial planning, incorporating resource availability, environmental quality, and social dimensions. However, implementation is inconsistent; only 8 of 34 provinces have completed comprehensive ECC assessments, and where

completed, results are often disregarded in licensing decisions [27], [28], [29], [30].

A 2023 assessment of the Yellow River Basin analogue in Indonesia – comparing peat-rich and mineral-soil watersheds in Kalimantan – exemplified methodological challenges. The study found that assimilative capacity for peat subsidence, peat fires, and peat-derived carbon emissions was exceeded at forest cover below 50% in peatland zones, contradicting the national 30% benchmark. Moreover, supportive capacity for water resources varied from 40% to 70% forest cover depending on topography and soil type. These findings underscore that a "one-size-fits-all" ECC threshold is scientifically unjustifiable and highlight the necessity for landscape-specific assessments [5].

Data gaps impede robust ECC quantification. Indonesia lacks comprehensive, high-resolution hydrological monitoring networks in many oil palm regions; only 42% of major rivers have baseline water quality and discharge data. Soil carbon inventories remain incomplete, with peatland carbon stock estimates ranging from 800 to 2,400 tonnes C ha⁻¹ depending on assessment method. Biodiversity surveys are similarly fragmented, limiting precise carrying capacity thresholds for species persistence. These data limitations mean that ECC assessments often rely on regional proxies or expert judgment, reducing their policy credibility [31].

Carbon Sequestration Capacity and Climate Regulation

1. Carbon Stocks in Oil Palm vs. Forest and Other Land Uses

Carbon sequestration capacity – the ecosystem's ability to accumulate and store atmospheric carbon – varies dramatically across land uses. Primary tropical forests in Indonesia accumulate 150–250 tonnes C ha⁻¹ aboveground and 100–300 tonnes C ha⁻¹ belowground, for total stocks of 250–550 tonnes C ha⁻¹. Oil palm plantations, by contrast, store only 30–80 tonnes C ha⁻¹ aboveground (biomass of mature palms, leaf litter) and accumulate negligible soil carbon due to soil disturbance and frequent tillage. The carbon deficit from forest-to-oil-palm conversion is therefore 170–520 tonnes C ha⁻¹, representing an immediate carbon loss equivalent to 600–1,900 tonnes CO₂ ha⁻¹ when converted to CO₂-equivalent emissions [32].

On mineral soils, this carbon loss is one-time; oil palm plantations can function as modest carbon sinks, sequestering 2–5 tonnes C ha⁻¹ yr⁻¹ in plantation biomass and soil recovery. Over a 25-year rotation, this yields cumulative sequestration of 50–125 tonnes C ha⁻¹, offsetting only 10–25% of the initial conversion loss. However, on peatlands, the carbon balance is fundamentally different. Peat soils contain 40–60% organic matter, encoding millennia of carbon accumulation. Drainage for oil palm cultivation lowers the water table by 0.5–1.5 m, triggering aerobic decomposition of peat and sustained carbon losses of 10–20 tonnes C ha⁻¹ yr⁻¹. Over a 25-year rotation, peatland oil palm plantations generate cumulative emissions of 250–500 tonnes C ha⁻¹, rendering them substantial net carbon sources despite modest aboveground sequestration [33].

A 2021 meta-analysis synthesizing 47 studies found that net greenhouse gas emissions from peatland oil palm averaged 8–15 tonnes CO₂-eq ha⁻¹ yr⁻¹, accounting for soil CO₂ emissions, N₂O from fertilizer, and occasional peat fires. In comparison, forest-to-oil-palm conversion on mineral soils yields net

emissions of 15–25 tonnes CO₂-eq ha⁻¹ yr⁻¹ for the first 5–10 years post-conversion (as initial biomass decay dominates), declining to 2–5 tonnes CO₂-eq ha⁻¹ yr⁻¹ as the plantation matures. These findings underscore that oil palm cannot be positioned as a climate solution unless restricted to degraded mineral soils and coupled with complementary forest protection and restoration [34].

2. Sustainable Expansion Ceilings and National Climate Commitments

Indonesia's Nationally Determined Contribution (NDC) under the Paris Agreement commits to reducing GHG emissions by 29–41% by 2030 relative to 2010 levels, with a target for the forestry, land use, and agriculture (FOLU) sector to achieve net-zero emissions (FOLU Net Sink 2030). However, current trajectories suggest this target is unattainable without dramatic shifts in palm oil policy. Between 2015 and 2023, FOLU emissions averaged 1,800–2,200 MtCO₂-eq yr⁻¹, driven predominantly by peatland drainage (60%), forest conversion (25%), and agricultural emissions (15%). If palm oil expansion continues at current rates (500,000–700,000 hectares yr⁻¹), half directed to peatlands, FOLU emissions will increase to 2,500 MtCO₂-eq yr⁻¹ by 2030, rendering climate targets unachievable [35], [36], [37].

Analysis of sustainable expansion ceilings reveals that to meet both climate targets and rising palm oil demand, the sector must operate within strict constraints. A 2022 study estimated that sustainable palm oil production in Indonesia—defined as growth achieved exclusively on degraded mineral soils without deforestation or peat conversion—can reach 45–50 million tonnes by 2045, meeting projected domestic and export demand. This would require zero expansion on peatlands and primary forests, intensification on existing plantations to 4.5–5 tonnes ha⁻¹ yr⁻¹ (vs. current 3.5 tonnes ha⁻¹ yr⁻¹), and restoration of 2–3 million hectares of degraded land currently idle. Critically, achieving these yields within climate-safe limits is technically feasible; the challenge is governance and enforcement [6].

3. Hydrological Functions and Disaster Mitigation

1. Effects of Forest-to-Oil-Palm Conversion on Water Regimes

Hydrological responses to land-use change are well-documented. Forest ecosystems in Indonesia intercept 15–25% of rainfall through canopy processes, facilitate infiltration rates of 5–15 mm hr⁻¹, and sustain dry-season baseflow through groundwater discharge. Oil palm plantations, with lower canopy density and simplified structure, intercept only 5–10% of rainfall, reduce infiltration to 1–3 mm hr⁻¹, and exhibit rapid surface runoff during storms. These hydrological shifts have cascading impacts [38].

Field experiments in Jambi and Riau provinces quantified these changes. A 2020 paired-watershed study in Jambi found that conversion of 60% of a watershed from forest to oil palm increased peak discharge by 35–50% and reduced dry-season baseflow by 25–35%. Flood duration extended from 2–3 days to 4–6 days, causing agricultural losses and infrastructure damage. Similarly, a 2022 study in a Kalimantan peatland watershed showed that drainage for oil palm reduced water table elevation by 0.8 m on average, triggering peat subsidence of 2–4 cm yr⁻¹ and increasing flood frequencies in adjacent communities. Modeling studies using hydrological models (SWAT+, HEC-HMS)

projected that if current forest loss trends continue, flood return periods in major Indonesian oil palm regions will decrease from 50-year events to 10-year events by 2050 [39].

Water quality degradation accompanies hydrological changes. Oil palm plantations contribute nutrient runoff (N, P), agrochemical residues, and sediment loads that degrade water quality. Monitoring of rivers in Sumatra revealed that phosphorus concentrations increased 5–10-fold and nitrogen 3–5-fold in reaches draining oil palm landscapes compared to forested reaches. These nutrient loads trigger eutrophication in downstream reservoirs and coastal waters, reducing water supply reliability and fisheries productivity [38].

2. Interactions with Drought, Fire Risk, and Peat Subsidence

Oil palm's hydrological vulnerability to drought compounds water stress. During dry seasons, oil palm requires consistent irrigation of 8–12 mm week⁻¹ to maintain fruit set and prevent yield penalties. In water-scarce regions, this competes directly with domestic supply and food crop irrigation. A 2024 analysis in Central Kalimantan documented that during the 2023 El Niño drought, agricultural water deficits reached 150 mm over a 6-month dry season, forcing rationing between oil palm, rice paddies, and urban supplies; oil palm received priority, exacerbating food insecurity [40].

Fire risk escalates in oil palm landscapes, particularly on peatlands. Drained peatlands become highly flammable; peat fires in 1997–1998 and 2015, concentrated in oil palm zones, burned 2.6 and 2.6 million hectares respectively, releasing 1.4–1.6 Gt CO₂ yr⁻¹. Although fires are often attributed to El Niño climate variability, anthropogenic drainage creates the precondition for catastrophic burning. Peatland oil palm plantations are 10–15 times more fire-prone than intact peatland forests. The 2015 fire season cost Indonesia an estimated USD 16 billion in damages and health impacts, with oil palm plantation drainage identified as the primary driver [31].

Peat subsidence represents an underappreciated consequence of drainage. Drainage-induced compaction and peat decomposition cause land surface subsidence at rates of 2–4 cm yr⁻¹ in oil palm plantations on peat. Over 25 years, this accumulates to 0.5–1.0 m subsidence, rendering coastal peatlands increasingly vulnerable to tidal inundation and saltwater intrusion. A 2023 study in Riau Province projected that by 2050, 40% of oil palm on peatland will be permanently inundated or severely waterlogged due to subsidence, effectively removing these lands from production and creating ecological wastelands [41].

3. Role of Riparian Reserves, Wetlands, and Agroforestry in Hydrological Restoration

Evidence from landscape experiments demonstrates that strategic riparian buffers, wetland set-asides, and agroforestry can restore hydrological functions. Riparian forest buffers of 50–100 m width reduce nutrient and sediment runoff by 60–80%, attenuate peak discharge by 15–25%, and maintain dry-season baseflow by facilitating groundwater recharge. In Southeast Asia, riparian restoration in oil palm landscapes increased fish diversity by 30–50% and downstream water quality indices by 40–60% [10], [42], [43], [44].

Agroforestry systems—integrating trees with oil palm or food crops—offer intermediate benefits. A 2022 meta-analysis of 23 agroforestry studies in Indonesia found that systems with 10–20% tree canopy cover maintained 70–80% of hydrological regulation services of native forest, sequestered 15–30 tonnes C ha⁻¹ over 25 years (compared to 2–5 tonnes in monoculture oil palm), and sustained 40–60% of forest biodiversity. Adoption by Indonesian smallholders remains limited (estimated at 5–8% of oil palm area), constrained by crop-lien systems that prioritize oil palm output and limited market pathways for agroforestry products. Policy interventions promoting agroforestry—via subsidized tree seedlings, technical support, and premium market prices—show promise but require sustained investment [45].

4. Ecological Integrity and Biodiversity Functions

1. Biodiversity Loss and Habitat Fragmentation in Oil Palm Frontiers

Oil palm expansion has been identified as a leading driver of tropical biodiversity loss. Indonesia hosts 10–12% of global species, with 50% endemic to threatened tropical forests. Oil palm plantations eliminate 90–99% of the original fauna and flora; a meta-analysis of 65 biodiversity studies found that species richness in oil palm plantations averaged 5–15% of that in primary forests. For iconic species, losses are even more severe. Orangutan populations in Sumatra and Borneo have declined by 80% over 20 years, with oil palm expansion the primary cause; only 6,300–7,300 orangutans remain in the wild, confined to fragmented forest reserves [1].

Landscape fragmentation compounds biodiversity loss. Oil palm plantations reduce forest connectivity, creating isolated habitat patches too small to support viable populations of large carnivores, primates, and megafauna. In Kalimantan, landscape fragmentation has increased from a mean patch isolation distance of 2 km (year 2000) to 15 km (year 2023), reducing migration and genetic exchange. The cumulative impact across Southeast Asian oil palm regions is an estimated loss of 3.5–4.2 million hectares of forest habitat, equivalent to 15–20% of the region's remaining tropical forest [46].

Ecological functions—pollination, pest control, nutrient cycling—are severely degraded in oil palm monocultures. Pollinator diversity (bees, birds, bats) in oil palm plantations is 5–10% of forested areas, reducing fruit set and yield stability in adjacent food crops. Herbivore-predator dynamics collapse, allowing pest outbreaks; oil palm scale, bagworm, and other pests cause 5–15% yield losses annually in monoculture plantations, necessitating heavy pesticide use (10–15 kg ha⁻¹ yr⁻¹), which further degrades ecosystems [47].

2. Landscape Configurations Enhancing Ecological Value

Strategic landscape design can substantially enhance ecological outcomes within oil palm regions. Set-asides (protected areas within concessions), riparian reserves, and retained forest patches create habitat refugia and connectivity corridors. A 2023 study in Sumatra evaluated landscape scenarios varying forest set-aside from 0% to 40% across a 50,000-hectare oil palm concession; results showed that 20–25% forest cover maintained viable populations of endemic bird species and orangutans (using metapopulation models) while still supporting commercial oil palm yields of 3.2 tonnes ha⁻¹ (vs. 3.8 tonnes in monoculture) [48].

Agroforestry – intercropping oil palm with native trees, fruit species, or nitrogen-fixing legumes – offers biodiversity and carbon co-benefits. A 2022 study comparing monoculture oil palm (0% tree cover), simple agroforestry (10% native trees), and complex agroforestry (30% tree species, understory crops) found that species richness increased from 12 species in monoculture to 45 species in complex agroforestry (28% of forest richness). Similarly, carbon stocks increased from 5 tonnes ha⁻¹ in monoculture to 25 tonnes ha⁻¹ in complex agroforestry. Market prices for agroforestry products (rattan, honey, fruits, timber) add 15–25% to household income compared to monoculture oil palm, incentivizing adoption among smallholders [49].

Ecological corridors connecting forest reserves through oil palm landscapes facilitate species movement and genetic exchange. A spatial analysis of 12 oil palm provinces revealed that restoring 2–3% of plantation area as riparian corridors (10–20 m width) would restore landscape connectivity sufficient to sustain viable populations of medium-sized carnivores and primates. Cost estimates for corridor establishment (tree planting, protection) range from USD 500–1,500 ha⁻¹, or approximately USD 2–5 billion for Indonesia-wide implementation, offset by ecosystem service values (carbon, water regulation, biodiversity) estimated at USD 8–15 billion over 25 years [48].

3. Socio-Ecological Impacts on Local and Indigenous Communities

Oil palm expansion has profound socio-ecological consequences for Indigenous peoples and local communities. An estimated 40 million Indigenous and local community members in Southeast Asia depend on tropical forests for subsistence and livelihoods; oil palm conversion reduces forest access, undermining food security, medicine, and cultural practices. Documentation of 350+ land conflicts in Indonesian oil palm regions reveals patterns of inadequate community consultation, disputed customary land rights, and restricted access to remaining forests. Women, who traditionally manage forest gardens and wild food collection, experience disproportionate livelihood losses [50].

Water conflicts emerge as oil palm expands. In Jambi, Riau, and Central Kalimantan, irrigation by oil palm plantations during dry seasons has exacerbated water scarcity for adjacent rice paddies and domestic supplies, triggering social tensions and crop failures. A 2020 study documented 47 water-related conflicts in oil palm regions, 38 involving irrigation competition. Conversely, flood and landslide risks in oil palm landscapes endanger downstream communities; hydrological modeling suggests that 2.5–3.5 million people in oil palm-dominated watersheds face increased flood hazards [51].

Climate justice dimensions are significant. Indonesian oil palm's carbon footprint – estimated at 8–12 tonnes CO₂-eq per tonne of oil when accounting for peatland emissions – exceeds the global food system average and contributes disproportionately to climate change, affecting global communities already vulnerable to climate impacts. Conversely, climate-vulnerable communities in oil palm regions (coastal and lowland populations) face compounded risks from both oil palm-induced hydrological changes and broader climate warming [23], [52], [53], [54].

5. Multi-Commodity Land Suitability and Spatial Allocation

1. Methods: GIS-Based Land Evaluation, MCDA, and Matching Approaches

Multi-commodity land suitability assessment is a systematic approach to match land characteristics with crop requirements, optimizing spatial allocation. The framework typically involves four steps: (1) land characterization (mapping of soil, topography, climate, hydrology); (2) crop requirement definition (based on agronomic and environmental data); (3) matching analysis using GIS overlay and multi-criteria decision analysis (MCDA); and (4) suitability classification (highly suitable, S1; moderately suitable, S2; marginally suitable, S3; unsuitable, N) [55].

Suitability criteria vary by commodity. Oil palm thrives on slopes $<8^\circ$, with deep soils (>1 m), rainfall 1,500–3,000 mm yr^{-1} , and good drainage; it tolerates moderate acidity (pH 4.5–6.5) and nutrient limitations (managed via fertilizer). Rice paddies require slopes $<3^\circ$, high soil moisture retention, rainfall $>1,200$ mm, and neutral to slightly acidic soils; perennial crops (rubber, coconut) require intermediate slopes and moderate drainage. Forests, from an environmental service perspective, should occupy steep slopes ($>20^\circ$), riparian zones (buffer width ≥ 50 –100 m), and high conservation value areas (biodiversity hotspots, carbon-dense peatlands) [56].

Indonesian studies applying MCDA to multi-commodity allocation have been conducted in seven provinces (Sumatra, Kalimantan, and Sulawesi). A 2024 study in Riau Province used Analytic Hierarchy Process (AHP)-MCDA to allocate 5 million hectares among oil palm, food crops (rice, maize), agroforestry, forestry, and urban-infrastructure uses, incorporating ecological, economic, and social criteria. Results indicated that 1.8 million hectares were highly suitable for oil palm, 1.2 million for food crops, 1.0 million for agroforestry, and 0.8 million required forest/conservation status. However, current land use reflects different proportions: 2.1 million hectares (42%) oil palm, 0.6 million hectares (12%) food crops, 0.4 million hectares (8%) agroforestry, 1.5 million hectares (30%) forest/protection. This mismatch—excess oil palm, deficit food crops—demonstrates misallocation relative to land suitability [57].

2. Evidence on Suitability for Oil Palm, Food Crops, Forestry, and Other Commodities

Spatial analysis across Indonesia reveals substantial tracts of degraded land with high suitability for agriculture that remain underutilized. An estimated 2.4–3.2 million hectares of mineral-soil degraded land (formerly forest or fallow) meet S1/S2 suitability for oil palm but remain idle, occupied by stunted forest regrowth, grassland, or informal settlements. Conversely, 1.5–2.0 million hectares currently under oil palm are classified as S3 (marginally suitable) or N (unsuitable), with profitability constrained by nutrient limitations, waterlogging, or steep slopes. These classifications suggest that reallocation from marginal to suitable land could increase productivity while freeing suitable food crop lands currently occupied by oil palm [58].

Food crop suitability presents a different pattern. High-suitability rice land (S1) is concentrated in volcanic lowlands (North Sumatra, West Java) and recent alluvial floodplains; total S1 area is approximately 3.2–3.8 million hectares,

matching current irrigated rice area (3.5 million hectares). However, 1.2–1.6 million hectares of S2 land for food crops (rainfed rice, maize) in Sumatra and Kalimantan have been converted to oil palm, reducing food crop production capacity and increasing import dependency. Restoring these lands to food crops through land reallocation could increase domestic rice production by 4–6 million tonnes (meeting 60–75% of projected 2045 demand shortfalls under climate change impacts) [59].

Agroforestry suitability is extensive in upland and transitional zones. Approximately 4.0–5.5 million hectares of land on slopes 8–20° and in areas with intermediate rainfall (1,200–1,800 mm) are suitable for agroforestry combining oil palm/cocoa with timber and fruit trees. Yet only 0.3–0.4 million hectares currently operate under agroforestry; market incentives, technical knowledge, and policy support are limiting factors [15].

3. Optimising Land Allocation: Degraded Land, Zoning Restrictions, and Planning Coherence

Optimization analyses suggest that Indonesia can meet projected 2045 demands for palm oil (60 million tonnes), food crops (self-sufficiency in rice, corn, soybeans), and forest conservation through strategic land reallocation. A World Bank-led optimization model integrating biophysical suitability, economic returns, carbon stocks, and biodiversity constraints concluded that a development scenario with zero new deforestation and zero peat conversion could achieve 48–55 million tonnes palm oil by 2045 (meeting demand) by: (1) reallocating 1.2–1.6 million hectares from marginal oil palm to S1/S2 food crop land; (2) intensifying oil palm on suitable mineral-soil plantations to 4.5–5.0 tonnes ha⁻¹ yr⁻¹; (3) restoring 1.8–2.4 million hectares of idle degraded land to oil palm; and (4) protecting and restoring 2.5–3.0 million hectares of forest and peatland [3], [55], [60].

Implementation requires robust spatial planning instruments. Indonesia's Rencana Tata Ruang Wilayah (RTRW, spatial layout plan) provides the legal framework, but enforcement is inconsistent; 60% of oil palm expansion between 2015 and 2023 occurred in zones designated for conservation or food crops in approved RTRW documents. Strengthening institutional capacity (provincial spatial planning offices), aligning sectoral policies (forestry, agriculture, environmental), and embedding environmental carrying capacity assessments into licensing procedures are critical gaps [16].

Private sector engagement in spatial optimization is emerging. Several major oil palm companies have adopted high-conservation-value/high-carbon-stock (HCV/HCS) frameworks, restricting expansion to degraded land and engaging in landscape planning with governments and communities. The CIFOR Trade Hub analysis identified that supply-chain-driven sustainability initiatives, coupled with jurisdictional approaches in Riau and Central Kalimantan, have reduced forest conversion rates by 40–60% in participating regions. However, these remain pockets of progress; system-wide transformation requires policy binding all producers [11].

6. Ideal Proportions of Forest, Food, Oil Palm, Infrastructure, and Other Uses

1. Legal and Scientific Benchmarks for Forest Cover

The Indonesian legal mandate for minimum forest cover – 30% of each river basin or island – is codified in the 1999 Forestry Law (Law No. 41/1999) and operationalized through Government Regulation No. 34/2004 on Forest Resource Management. This benchmark originated from hydrological research in the 1970s–1980s, suggesting that 30% forest cover is necessary to maintain baseflow and moderate flood peaks in tropical monsoon watersheds. However, empirical evidence from the past two decades refines and complicates this threshold [12], [61].

Tarigan et al.'s 2018 hydrological modeling study, examining 23 Indonesian watersheds, found that optimal forest cover for minimizing flood and drought risk varies from 35% in low-relief mineral-soil watersheds to 60–70% in peat-dominated steep watersheds. Peatland hydrology is particularly sensitive; a 2022 meta-analysis of peatland carrying capacity concluded that forest cover below 50% in peat zones triggers irreversible subsidence and fire risk, rendering the 30% benchmark inadequate for peatland regions. Furthermore, the 30% target is often misinterpreted as a ceiling rather than a floor; several provinces have allowed forest cover to decline to 20–25% in specific landscapes without corresponding compensatory protection elsewhere [7], [31].

Contemporary policy discourse in Indonesia recognizes these limitations. The 2020 Forest and Land Fire Prevention Strategy and the 2021 National Action Plan for GHG Reduction both reference the need for landscape-specific forest cover targets exceeding 30% in vulnerable regions. However, operationalization remains weak; legal reforms establishing differentiated forest cover targets (40–50% for mineral-soil lowlands, 60–75% for peatlands) have been proposed but not yet enacted [31].

2. Conceptual Scenarios for Forest-Food-Oil Palm-Infrastructure Proportions

Spatially explicit land-allocation scenarios provide a framework for determining ideal proportions. The World Bank's Sustainable Lowland Agriculture Development study (2021) modeled five scenarios for a representative lowland province (Jambi, 5.2 million hectares) with differing priorities:

Scenario 1 (Business-as-usual): Current trends continue; 45% oil palm, 35% forest (declining), 12% food crops, 8% other. Result: forest cover falls below 25%, carbon emissions exceed 250 MtCO₂-eq, and food production declines 15% by 2045 due to climate impacts on remaining agricultural land [62].

Scenario 2 (Climate-safe oil palm): Zero peat conversion, zero primary forest loss, intensification of existing plantations. Result: 42% oil palm (on degraded mineral soils and existing plantations), 38% forest, 13% food crops, 7% other. Achievement requires a 15-year moratorium on new plantations, intensification to 4.5 tonnes ha⁻¹, and restoration of 400,000 hectares. Palm oil production reaches 32 million tonnes by 2045 (within sustainable limits), food self-sufficiency is achieved, and carbon emissions decline 40% by 2050 [34].

Scenario 3 (Landscape diversity): 38% oil palm, 42% forest, 15% food crops, 5% agroforestry/other. Result: enhanced biodiversity and ecosystem services

(hydrological regulation, carbon storage). Palm oil production reaches 28 million tonnes (meeting domestic demand but not exports), but biodiversity persistence increases to 65% of baseline forest levels; livelihoods more diversified through agroforestry and crop variety [63].

Scenario 4 (Food security priority): 25% oil palm, 40% forest, 28% food crops, 7% other. Result: food self-sufficiency assured; palm oil production limited to domestic consumption (~12–15 million tonnes), requiring export reduction and economic restructuring but maximizing nutrition and livelihood resilience [59]. These scenarios illustrate fundamental trade-offs. Scenarios 2 and 3 represent feasible pathways within ecosystem carrying capacity, reconciling palm oil economic interests with climate and biodiversity objectives. Scenario 4 prioritizes food security and resilience over commodity exports. All scenarios assume robust governance, effective enforcement, and stakeholder commitment – areas where Indonesia faces institutional limitations [11].

3. Regional Differentiation: Peat vs. Mineral, Frontier vs. Consolidated

Optimal proportions vary significantly by landscape context. In peat-dominated regions (Riau, Central Kalimantan, parts of Jambi and South Sumatra), the carrying capacity for agricultural commodities (oil palm, food crops) is substantially lower than in mineral-soil lowlands due to rapid carbon loss, subsidence, and fire risk. Scientifically grounded recommendations suggest: 60–70% forest/wetland protection, 15–20% agroforestry, 5–10% oil palm on mineral-soil inclusions, 10–15% food crops on suitable areas, 5% infrastructure. Current allocations in peat regions (often 40–50% oil palm, 20–30% forest) exceed carrying capacity and generate cumulative emissions incompatible with climate targets [64].

In mineral-soil lowlands (North Sumatra, Southeast Sulawesi, parts of West Kalimantan), forest cover norms can be lower (30–40%) while sustaining hydrological functions, provided riparian buffers and set-asides are protected. Scenario 2 allocations (42% oil palm, 38% forest, 13% food crops) represent a reasonable balance. In frontier regions where land tenure remains contested and governance is weak (Papua, Maluku), a precautionary approach suggests higher forest allocation (60–70%) to allow time for institutional development and customary rights recognition; rapid commodity expansion risks environmental and social catastrophe [8].

In consolidated regions with mature infrastructure and established tenure (Central Java, East Java, parts of North Sumatra), land proportions can reflect comparative advantage; oil palm is often less suitable than food crops or agroforestry due to climate and soil constraints, and forest cover is naturally lower (15–25%) in deeply settled landscapes [65].

DISCUSSION

1. Synthesising Ecosystem Carrying Capacity for Sustainable Palm Oil

The evidence synthesized above reveals a fundamental misalignment between current palm oil expansion trajectories and regional ecosystem carrying capacity across Indonesia. Land carrying capacity—measured by available suitable degraded land—has plateaued; water resources face mounting stress in major palm oil provinces; carbon sequestration capacity is exhausted on peatlands and rapidly declining on mineral soils; hydrological regulation is compromised in 40–50% of oil palm landscapes; and ecological integrity has been severely degraded in most consolidated production zones [2], [31].

Integrating these dimensions into a unified ECC framework reveals that Indonesia's palm oil sector cannot achieve simultaneous growth in production, forest protection, food security, and climate mitigation under current governance and technological regimes. Instead, there exists a feasible solution space—what Scenario 2 approximates—in which the sector achieves economic viability and moderate growth (to 45–50 million tonnes by 2045) by shifting from area-based expansion to productivity-based intensification, strictly protecting high-carbon and high-conservation-value landscapes, and engaging in landscape-level restoration [11], [49].

This reframing has three critical implications. First, the notion that "sustainable palm oil" requires finding "spare land" within existing deforestation trends is misconceived; the only truly sustainable expansion path is within genuinely degraded mineral-soil landscapes, estimated at 1.8–2.4 million hectares globally. Second, smallholder intensification and agroforestry represent underexploited pathways with comparable or greater profitability than monoculture oil palm on marginal land, yet face policy and market barriers. Third, the sector's resilience to climate change—critical for long-term viability—depends on restoring hydrological regulation and biodiversity buffering through landscape diversification; monoculture plantations become increasingly climate-vulnerable as drought and flood extremes intensify [25], [39].

2. Implications for Spatial Planning and Land-Use Governance

Embedding ECC analysis into spatial planning requires institutional and instrumental reforms. First, environmental carrying capacity assessments must become mandatory, legally binding components of spatial plans, replacing current advisory status. Assessments should be landscape-specific (watershed or landscape-scale), incorporate multi-hazard risk analysis (floods, fires, droughts), and be updated every 5–7 years as climate and land-use conditions evolve [2]. Second, sectoral policy coherence is essential. Currently, the Ministry of Agriculture targets 17–18 million hectares of oil palm by 2045; the Ministry of Environment targets forest protection; the Ministry of Food targets rice self-sufficiency; and the Ministry of Public Works manages infrastructure—without integrated planning or shared indicators. Inter-ministerial coordination mechanisms (e.g., National Land Agency with cross-sectoral authority) must align these objectives within ECC constraints [25].

Third, forest cover targets should be differentiated by landscape type. Peatland regions require 60–70% forest/wetland protection; mineral-soil lowlands can accommodate 30–40% forest if coupled with riparian buffers and set-asides; and frontier regions should adopt 60–70% as precautionary thresholds pending governance strengthening. Legal amendments to the Forestry Law and enactment of subsidiary regulations are necessary to operationalize these thresholds [11], [66].

Fourth, land tenure security and rights recognition are preconditions for effective spatial planning. Land conflicts, often arising from overlapping concession claims and unrecognized customary rights, undermine planning credibility and implementation. Rapid completion of customary land mapping and legal recognition of Indigenous land rights—currently covering <10% of Indigenous territories—would reduce conflicts and enable community-based landscape management [50], [67].

3. Design Principles for Multi-Commodity, Carrying-Capacity-Based Landscapes

Translating ECC frameworks into operational landscapes requires explicit design principles. The following are derived from evidence reviewed:

Principle 1: Ecological foundations. Landscapes must protect forest cover, wetlands, and riparian zones as ecological infrastructure, non-negotiable for hydrological stability, carbon storage, and biodiversity. Minimum protected area should equal or exceed landscape-specific forest cover targets (30–70% depending on soil and topography). These areas are spatially prioritized based on: (a) carbon density (peatlands, peat-forest transitions); (b) biodiversity richness (endemic species concentrations); (c) hydrological importance (headwaters, riparian zones); and (d) disaster-mitigation value (slopes >20°, flood-prone areas) [5], [31].

Principle 2: Agricultural productivity optimization. Agricultural lands are allocated to commodities based on highest suitability and profitability, not default expansion. High-suitability land for food crops (rice, maize) is protected from oil palm conversion. Oil palm expansion is confined to S1/S2 mineral-soil degraded land; S3 plantations on unsuitable land are candidates for reallocation. Intensification of existing plantations to 4.5–5.0 tonnes ha⁻¹ yr⁻¹ is prioritized over area expansion, achievable through improved agronomy, harvesting efficiency, and crop breeding [15].

Principle 3: Agroforestry integration. Intermediate-suitability land (slopes 8–20°, marginal fertility) is allocated to agroforestry systems integrating oil palm, timber, fruit, and nitrogen-fixing trees. Agroforestry generates 70–80% of hydrological services, 50–60% of carbon storage, and 40–50% of biodiversity persistence of native forests, while supporting farm livelihoods and food security. Policy incentives (subsidized planting material, technical training, premium markets) and institutional support (farmer organizations, extension) are essential for scaling [25], [47].

Principle 4: Landscape connectivity. Set-asides, riparian corridors, and restored forest patches are strategically positioned to maintain ecological connectivity. Minimum corridor width should be 10–20 m for riparian buffers (supporting fish and aquatic invertebrates) and 50–100 m for forest corridors (allowing terrestrial

fauna movement). At the landscape scale (>50,000 hectares), >15% of land should be in connected protected or agroforestry land to maintain viable populations of large fauna [10], [25].

Principle 5: Climate adaptation and resilience. Landscape design incorporates climate-risk analysis, prioritizing diversified land use (food crops, oil palm, agroforestry, forest) over monoculture, enhancing adaptive capacity. Water retention and infiltration capacity are maximized through riparian restoration and agroforestry, buffering against drought and flood extremes [25], [68].

4. Research Gaps and Future Directions

Despite the substantial literature reviewed, significant knowledge gaps limit ECC operationalization. First, the temporal dynamics of carrying capacity remain poorly understood. How do ECC thresholds shift under climate change? Do peatland fire cycles render 30-year-old carbon stock estimates obsolete? How does landscape history (prior land use, disturbance recovery) influence current carrying capacity? Longitudinal studies spanning 15–20 years with consistent methodology are needed [27], [31], [32].

Second, integrated modeling coupling hydrology, carbon, biodiversity, and social outcomes remains underdeveloped. Most studies examine single dimensions; the few integrated models (e.g., landscape optimization models) rely on simplified biodiversity metrics and omit livelihood dynamics. Development of open-source, spatially explicit models coupling hydrological, carbon, and socio-economic processes would enhance planning support [17].

Third, smallholder system dynamics are underrepresented. Seventy percent of Indonesia's oil palm area is on smallholder land; yet research disproportionately focuses on industrial plantations. Smallholder agroforestry, land-use transitions, and livelihood pathways warrant intensive study to identify scaling opportunities and governance models [1], [11], [25].

Fourth, peatland restoration economics and hydrology need refinement. Current knowledge on peat rewetting, carbon sequestration rates, and hydrological recovery post-restoration is based on limited field data. Demonstration projects across diverse peat types and climates would advance restoration feasibility assessment [31], [64].

CONCLUSIONS AND RECOMMENDATIONS

1 Substantive Conclusions

This qualitative literature review demonstrates that regional ecosystem carrying capacity—encompassing land, water, carbon, hydrological, and ecological dimensions—is a powerful, scientifically grounded framework for guiding sustainable palm oil development in Indonesia. Current expansion trajectories exceed these carrying capacities in most lowland regions, particularly peatlands, where rapid carbon loss, subsidence, fire risk, and hydrological degradation render continued large-scale expansion ecologically and climatically untenable. Evidence suggests that oil palm can operate within ecological thresholds if development is confined to genuinely degraded mineral soils, existing plantations are intensified from 3.5 to 4.5–5.0 tonnes ha⁻¹ yr⁻¹, and landscape-level restoration and protection are prioritized.

The integration of land suitability assessments, hydrological modeling, carbon accounting, and biodiversity analysis reveals substantial opportunities for optimizing land allocation. Indonesia can meet projected 2045 demands for palm oil (45–55 million tonnes, sufficient for domestic consumption and sustainable exports), food crops (rice, corn, soybean self-sufficiency), and forest protection while reducing GHG emissions 40–50% below current levels—provided governance and policy frameworks align around ECC-based spatial planning. Legal forest cover benchmarks, currently set at 30%, are scientifically adequate for mineral-soil lowlands but insufficient for peatlands and steep topography, necessitating landscape-specific differentiation (30–40% for mineral lowlands, 60–70% for peatlands and steep watersheds).

Agroforestry, despite limited current adoption, represents an underexploited pathway combining livelihood resilience, climate adaptation, and modest production. Scaling agroforestry from 0.3–0.4 million hectares to 2.0–3.0 million hectares by 2045, coupled with food crop area recovery and peatland protection, would align land use with ECC constraints while enhancing ecosystem services and community well-being.

2. Policy and Policy Recommendations

The following recommendations are offered for Indonesian policymakers, with international relevance for other tropical oil palm producers:

Recommendation 1: Establish a regulatory framework for environmental carrying capacity assessment. Mandate ECC assessments as binding components of provincial spatial plans, updated every 5 years, with standardized metrics, transparent modeling, and public participation. Differentiate forest cover targets: 30–40% for mineral-soil lowlands (with riparian buffers), 60–70% for peatlands, and 60–70% for frontier regions. Embed ECC thresholds into licensing criteria for oil palm concessions, effectively creating a "carrying capacity budget" of available suitable land per province.

Recommendation 2: Implement a 15-year moratorium on new peatland conversion. Given peatlands' climate significance and the availability of 1.8–2.4 million hectares of suitable degraded mineral-soil land, new peatland development is incompatible with national climate commitments. During the moratorium, support peatland restoration through financial incentives (blue carbon finance), policy clarification on customary peatland rights, and demonstration projects. Extend moratorium to primary and secondary forest, operationalizing the Zero Deforestation, Zero Peat, No Exploitation (ZDPP) commitment.

Recommendation 3: Reallocate land from marginal oil palm to high-suitability food crops. Identify the 1.5–2.0 million hectares currently under oil palm classified as S3/N (marginally/unsuitable), target for reallocation to food crop production or agroforestry. Couple with incentive programs (land consolidation, crop insurance, input subsidies) to support farmer transition. Target reallocation of 800,000–1.0 million hectares by 2035, recovering 4–6 million tonnes annual food production capacity.

Recommendation 4: Accelerate oil palm intensification on suitable land. Set a target for average yields to increase from 3.5 to 4.5 tonnes ha⁻¹ FFB by 2035, achievable through improved seedlings (improved germplasm, disease

resistance), agronomic practices (soil management, precision fertilization), and technology (drone monitoring, yield prediction models). Funding mechanisms could include carbon finance (linking yield improvement to emissions reduction), certification premium reinvestment, and green lending from development banks.

Recommendation 5: Scale agroforestry to 2.0–2.5 million hectares by 2045. Establish subsidy schemes for tree seedling provision, technical extension, and premium market development for agroforestry products. Support farmer cooperatives and value chains for agroforestry output (timber, fruit, honey, rattan). Pilot agroforestry in 200,000–300,000 hectares by 2030, with monitoring of carbon, water, and biodiversity co-benefits. Target agroforestry adoption on 30–40% of current S3 plantation land and on food crop-oil palm transitions.

Recommendation 6: Strengthen inter-ministerial governance and spatial planning coherence. Establish a cross-ministerial land-use coordination body (hosted by the National Land Agency or Coordinating Ministry) with authority to align sectoral targets within ECC constraints. Develop a shared land-use database integrating forestry, agriculture, and environmental data at 25–30 m spatial resolution, updated annually. Institutionalize multi-stakeholder landscape dialogues at the provincial level, including government, private sector, civil society, and Indigenous representatives, to resolve competing land claims.

Recommendation 7: Recognize and protect Indigenous and customary land rights. Accelerate legal recognition of Indigenous land rights, currently recognized for <10% of Indigenous territories. Customary land security underpins effective landscape management; conflict reduction and community-based conservation accelerate from customary rights formalization. Support implementation of Free, Prior, and Informed Consent (FPIC) standards for any development on customary land.

Recommendation 8: Align palm oil sector targets with climate and biodiversity commitments. Revise national palm oil production targets downward from the current projection of 60 million tonnes by 2045 to 45–50 million tonnes, reflecting ECC and carbon constraints. Coupled with incentives for domestic value-addition (refining, processing), reducing reliance on raw oil exports, and enhancing value capture. Align FOLU Net Sink 2030 targets explicitly with zero peatland conversion and forest protection, making oil palm policy subordinate to climate commitments.

3. Implications for Stakeholders and International Initiatives

Private sector actors—multinational and regional palm oil companies, traders, and financiers—face pressure from ESG-focused investors, sustainability certification schemes, and EU Deforestation Regulation compliance to operate within ecological thresholds. Forward-looking companies are adopting HCV/HCS frameworks and jurisdictional approaches, reducing deforestation rates in participating regions by 40–60%. However, laggard producers and investments in frontier regions continue to experience unsustainable expansion. Sector-wide transformation requires policy binding all producers, not voluntary corporate initiatives; governments must regulate.

International trade frameworks are relevant. The EU Deforestation Regulation (EUDR) and proposed Carbon Border Adjustment Mechanism (CBAM) create market incentives for low-deforestation, low-emission palm oil, benefiting producers adhering to ECC constraints. However, implementation risks include uneven application across supply chains and potential exclusion of small-scale producers lacking certification capacity. Capacity building for smallholders and development of inclusive certification schemes are necessary to prevent market marginalization.

Development partners and multilateral institutions (World Bank, ADB, Global Environment Facility) support ECC-based planning through technical assistance, financing of spatial planning and restoration initiatives, and policy dialogue. The UN Sustainable Development Goals (SDGs) 12 (sustainable production), 13 (climate action), 14 (life below water), and 15 (life on land) align with ECC-centered palm oil governance, creating pathways for integrated support.

Finally, civil society organizations—environmental NGOs, community organizations, Indigenous rights advocates—play essential roles in monitoring compliance, facilitating multi-stakeholder dialogue, and holding governments and companies accountable. Strengthening civil society capacity in land rights advocacy, spatial data analysis, and community monitoring will enhance governance robustness.

4. Concluding Remarks

Ecosystem carrying capacity offers a scientifically rigorous, normatively defensible framework for guiding sustainable palm oil development. Rather than viewing sustainability as a constraint on production, ECC reframes it as a foundation for long-term sector viability. Monoculture expansion on fragile lands generates short-term profits offset by externalized ecological and climate costs, creating long-term liabilities. In contrast, intensification-based development within ECC constraints—protecting peatlands and forests, reallocating suitable land to high-yield commodities, scaling agroforestry, and restoring degraded landscapes—generates sustainable economic returns, climate resilience, and social equity.

Indonesia has a unique opportunity to operationalize ECC-based palm oil governance, demonstrating a model for tropical commodity development that reconciles production with ecological integrity. Realization requires political will, institutional capacity, and stakeholder alignment—significant but not insurmountable challenges. The scientific foundation is robust; the policy pathways are outlined; the technologies exist. **The decisive factor is implementation.**

FURTHER STUDY

This research still has limitations so that further research is needed on the topic of Regional Ecosystem Carrying Capacity and Sustainable Palm Oil Development: A Review on Land-Water-Carbon-Hydrological-Ecological Dimensions and Optimal Spatial Allocation to perfect this research and increase insight for readers and authors.

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