



# Sustainable Management Strategies for Oil Palm Plantations Based on an Analysis of Environmental Degradation in Tualang District, Riau

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**Abstract:** Land-use conversion from forests to oil palm plantations in Tualang District, Siak Regency, has intensified environmental and settlement pressures, requiring systematic evaluation. This study aims to analyse the spatial dynamics of forest conversion, assess environmental and settlement impacts, and formulate sustainable management strategies. A mixed-methods approach was employed, integrating spatial analysis of Landsat and Sentinel imagery, field surveys, observations, and in-depth interviews. Spatial change analysis and SWOT analysis were applied to interpret land-use dynamics and management options. The results indicate that from 2015 to 2025, oil palm expansion increased markedly, with forest and peatland conversion accounting for more than one-quarter of the total area. These changes led to soil degradation, biodiversity loss, increased runoff, water contamination, and reduced community access to natural resources. The proposed strategies emphasize conserving ecological buffers, strengthening community monitoring capacity, enforcing land-use regulations, and promoting sustainable plantation practices. Overall, integrated spatial planning and community participation are essential to ensure environmentally sustainable oil palm development.

**Keywords:** Environmental sustainability; Land use change; Management strategy; Oil palm; Spatial analysis; Tualang

## Introduction

Land-use change due to agricultural expansion is a central concern in sustainability science because it reshapes ecosystem functions, alters biogeochemical cycles, and undermines biodiversity and human well-being in tropical regions where forests are critical to climate regulation, species diversity, and local livelihoods (Wagner et al., 2022). In Indonesia, oil palm cultivation has become a dominant land-use trajectory, generating substantial economic benefits while simultaneously driving deforestation, peatland degradation, and greenhouse gas emissions (Oil palm boom and land-use dynamics in Indonesia (Xu et al., 2020). Governing sustainability: land use change impact on the palm oil industry in Riau Province, 2024 (Duke et

al., 2015). Scientific evidence demonstrates that expansion of oil palm plantations often replaces high-carbon forests and peatlands, leading to significant carbon release, loss of native habitat, and disruption of hydrological systems (Deforestation, plantation-related land cover dynamics in Riau Province Effects of soil subsidence on plantation agriculture in Indonesian peatlands (Hidayah, 2025). Remote sensing studies further reveal that plantation expansion has been a leading driver of forest loss in Sumatra and Kalimantan, undermining regional forest cover and biodiversity integrity (Juliano et al., 2024). Land-use transformation linked to oil palm also produces multifaceted socio-ecological impacts, such as reduced ecosystem services, altered soil fertility, and changes in species composition (Impact of converting sawah to oil palm on soil

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macrofauna (Schindler et al., 2021). At community scales, research reports show that conversion of natural and agricultural lands to plantations affects local water quality, traditional resource access, and rural livelihoods. In Riau Province, where peatland landscapes predominate, plantation development has intensified landscape fragmentation, increased fire and flood risks, and contributed to conflicts over land rights and governance (Rosana et al., 2023). Despite these documented patterns, most studies remain focused at the national or provincial level, with limited integrated spatial-environmental and socio-institutional analysis at the sub-district level. Few investigations utilise high-resolution remote sensing, combined with field surveys and stakeholder perspectives, to directly link the spatial dynamics of forest and peatland conversion to local ecological degradation and community vulnerability (Kamlun et al., 2024). Addressing this gap, the present study examines the spatial dynamics of forest conversion into oil palm plantations in Tualang District, evaluates the resulting environmental and settlement impacts, and formulates sustainability-oriented management strategies. The urgency of this research lies in advancing evidence-based land-use planning and integrated management approaches that balance economic development with ecological conservation and community resilience in peatland-dominated landscapes.

## Method

This study employed a mixed-methods research design integrating quantitative spatial analysis and qualitative inquiry to obtain a comprehensive understanding of land-use change, ecological impacts, and sustainable management strategies for oil palm plantations in Tualang District, Siak Regency, Riau Province. The study area was selected because of the rapid conversion of forest and peatland to industrial-scale oil palm plantations, making it representative of ongoing socio-ecological transformations.

Primary data were collected through field observations, household surveys, and in-depth interviews with community leaders, village officials, plasma farmers, and plantation representatives. Environmental observations focused on vegetation change, soil conditions, water quality, and landscape structure. Household surveys captured community perceptions of environmental degradation, livelihood impacts, and participation in conservation practices. Key informant interviews provided insights into land governance, sustainability certification, corporate environmental management, and local ecological challenges.

Secondary data consisted of Landsat 8 OLI and Sentinel-2 MSI imagery, land-use maps from BPS and DLHK, environmental reports, and regional spatial planning documents. Remote sensing and GIS techniques were applied to process and analyse satellite imagery, including geometric and atmospheric correction, radiometric calibration, and cloud masking. Land cover classification was conducted using supervised classification with the Maximum Likelihood algorithm, and classification accuracy was evaluated using confusion matrices and Kappa coefficients. Land-use change analysis for the 2015–2025 period employed raster overlay techniques and spectral indices, including NDVI and NDWI, to identify transitions from forest and peatland to oil palm plantations.

Qualitative data were analysed using Miles and Huberman's interactive model, comprising data reduction, data display, and conclusion drawing. Data triangulation across sources, methods, and datasets was applied to enhance analytical validity. Sustainable management strategies were formulated through SWOT analysis, in which internal and external factors were weighted and synthesised into the strategic categories of SO, WO, ST, and WT. This integrated methodological framework enabled the development of evidence-based strategies that incorporate ecological, social, and governance dimensions of sustainability in Tualang District.

## Result and Discussion

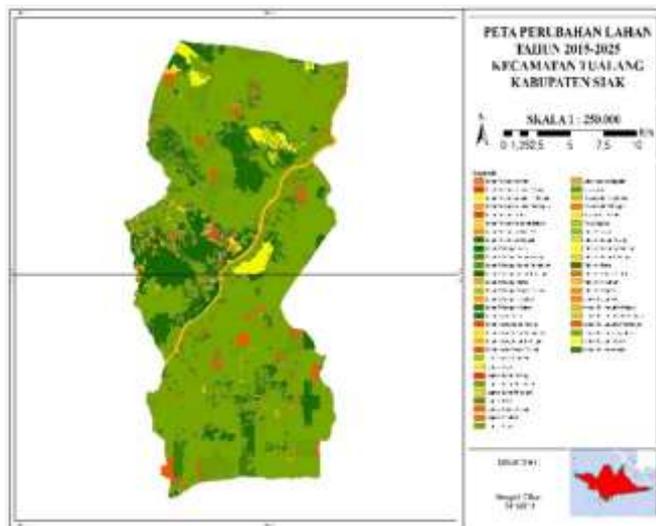
The rapid expansion of oil palm plantations in recent years has generated increasingly complex environmental and social challenges across tropical landscapes, including the Tualang District. Large-scale conversion of forests and peatlands has accelerated ecosystem degradation, reduced water retention capacity, and heightened the risk of seasonal flooding and drought. Recent studies highlight that peatland ecosystems are particularly vulnerable to land-cover change (Bell et al., 2021).

Documenting significant biodiversity loss and structural decline following intensive drainage and monoculture expansion. Similarly, Barnes et al. 2025 emphasize that shifts from natural forest to oil palm monoculture disrupt ecohydrological cycles and degrade soil quality (Barnes et al., 2014). On the social front, oil palm expansion has reshaped livelihoods by increasing economic dependence, altering land access, and creating new layers of inequality. Research indicates that environmental pressures in plantation-dominated regions tend to reduce community resilience, particularly where participatory land governance remains weak (Hergoualc'h et al., 2025). These interlinked ecological and socio-economic issues

underscore the need for a comprehensive investigation into how landscape transformation shapes environmental conditions and community wellbeing in Tualang, and why more sustainable management strategies are urgently required.

*Land Use Change Driven by Oil Palm Expansion*

Understanding land use change requires not only spatial observation but also an examination of the socio-economic dynamics that drive landscape transformation. In many tropical regions, shifts in land cover are strongly influenced by plantation expansion, settlement growth, and development pressures that alter ecological stability over time. Winkler et al. (2021) emphasize that land-use change is a key indicator of ecosystem responses to human activities and has substantial implications for hydrological regulation and environmental resilience. Similarly, Bukoski et al. (2022) note that large-scale conversion toward monoculture systems accelerates ecosystem degradation and contributes to significant biodiversity loss. These findings highlight the necessity of spatial mapping to identify where and how landscape alterations occur, especially in regions experiencing rapid land-use transitions. In the case of Tualang District, such an approach is essential for assessing ecological pressures and understanding the trajectory of landscape change over the past decade. Therefore, the following section presents an integrated analysis of land-cover change using the 2015 land-use map and the 2025 overlay results.



**Figure 1.** Land cover change map

Moreover, the overlay analysis of landscape change from 2015 to 2025 reveals a highly complex, multilayered pattern of transformation, closely aligned with the expansion of plantations and settlements in Tualang District. Based on the land-cover transition table, several

land-cover categories exhibited substantial functional shifts. One of the most notable changes is the conversion of vacant land into plantation areas, particularly in segments classified as "Open Land → Plantation." This pattern indicates a continuous process of intensification and expansion of oil palm cultivation, which has become the dominant land-use trend over the past decade. This shift is consistent with the spatial transformation observed in the 2025 map, where plantation areas increasingly replace vegetation and shrubland.

In addition, significant conversion occurred in wetland ecosystems, as shown by transitions such as "Swamp → Built-Up Area," "Swamp → Plantation," and "Swamp → Shrubland." These conversions demonstrate substantial pressure on wetland systems that previously served as natural hydrological buffers. The shift from swamp to plantation also reflects increasing degradation of peatland ecosystems, directly affecting water retention capacity, soil stability, and the risk of land and forest fires. These findings are consistent with those of previous studies who assert that the conversion of wetlands to monoculture plantations accelerates biodiversity decline and heightens ecosystem vulnerability.

Another notable trend is the transition of natural vegetation into built-up areas and plantations, as indicated by categories such as "Vegetation → Built-Up Area" and "Vegetation → Plantation." This pattern illustrates the gradual narrowing of natural vegetation cover due to increasing demand for residential space, infrastructure development, and production activities. (Liu et al., 2020) highlight that the loss of natural vegetation disrupts hydrological cycles, reduces soil moisture retention, and intensifies ecological stress across the landscape.

Shrubland also experienced substantial transitions, primarily through categories such as "Shrubland → Plantation" and "Shrubland → Built-Up Area," indicating that secondary vegetation areas have become primary targets for new land development. This transformation contributes to the decline of ecological buffer zones that function as habitat connectors and transitional ecosystems. Emphasize that the reduction of these ecological buffers weakens socio-ecological resilience in rapidly expanding plantation regions (Kurniadi, 2025).

The data further reveal several minor yet relevant changes, such as "Cloud → Water Body," "Cloud → Built-Up Area," and "Cloud → Vegetation." These categories generally correspond to areas obscured by cloud cover in the 2015 imagery that were successfully classified in the 2025 imagery. Although these changes do not reflect physical transformations, they remain important as indicators of improved classification accuracy in the updated land cover map.

Overall, the compilation of land cover changes demonstrates that oil palm expansion is the primary driver of landscape transformation in Tualang District during the 2015–2025 period. The widespread conversion of vegetation, wetlands, and shrubland into plantations and built-up areas signifies escalating ecological pressure and long-term implications for biodiversity, hydrological stability, and environmental resilience. Further studies note that such pressures extend to social dimensions, increasing community vulnerability through heightened economic dependency and reduced livelihood security (Astari et al., 2025). These findings collectively underscore the urgent need for sustainable land management strategies, wetland protection, and strengthened spatial governance to mitigate long-term ecological and social risks.

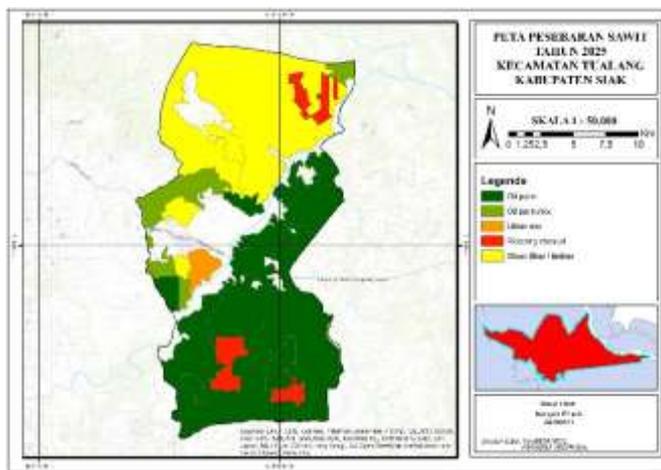


Figure 2. Oil palm distribution map

The 2025 oil palm distribution map reveals that Tualang District is predominantly occupied by extensive oil palm plantations, particularly in the southern and central zones, as indicated by the dark green areas (oil palm). This spatial pattern demonstrates that land conversion toward plantation development has reached an advanced stage of intensification. Such dominance is consistent with broader regional trends in Sumatra, where rapid plantation expansion has transformed previously forested and wetland landscapes. Emphasize that large-scale expansion of oil palm typically leads to substantial ecological degradation, including biodiversity loss and ecosystem (Azhar et al., 2023), which aligns with the spatial characteristics observed in this map. The distribution of oil palm mix (light green), concentrated primarily in the central part of the district, indicates transitional landscapes composed of mixed young plantations, residual vegetation, and partially cleared areas. These conditions commonly appear in regions undergoing gradual deforestation and early-stage plantation establishment. Transitional zones often correspond to disrupted ecohydrological processes,

increased surface runoff, and declining soil moisture stability

In the northern part of Tualang, the presence of wood fibre/timber (yellow) suggests that portions of the area are still managed as industrial forest plantations. However, adjacent recently cleared zones (orange) indicate new land clearing activities, potentially signalling future conversion into oil palm plantations. Note that sequential clearing of production forest areas frequently accelerates ecosystem service loss and heightens community vulnerability around plantation frontiers (Kellett et al., 2023).

Meanwhile, the presence of other mixed areas (red), especially in the southern region, reflects highly dynamic land-use transitions likely comprising degraded land, shrubland, and non-plantation activities. Such transitions often illustrate economic pressures and intensification processes around established plantation clusters. Studies highlight that extensive transitional zones weaken socio-ecological resilience due to reduced ecological buffers and limited community access to natural resources.

Overall, the 2025 oil palm distribution map shows that plantations occupy more than half of Tualang District’s landscape, with a clear expansion trajectory from the south toward the central and potentially northern areas (Mukhlis et al., 2025). This spatial pattern suggests a rapidly transforming landscape with heightened risks of ecological degradation, altered hydrological functions, and increasing social pressures on settlements located near plantation zones. These findings underscore the urgent need for strengthening ecological buffer protection, enhancing oversight of land clearing, and promoting sustainable oil palm management practices aligned with RSPO/ISPO standards throughout Tualang District.

#### Environmental Impacts

The expansion of oil palm plantations in Tualang District between 2015 and 2025 has generated a wide range of significant and interrelated environmental impacts. The most prominent impact is deforestation and peatland degradation, which reduces carbon storage capacity and increases greenhouse gas emissions. Studies indicate that peat conversion for oil palm cultivation can release up to 56–73 tons of CO<sub>2</sub> ha<sup>-1</sup> per year (Qu et al., 2020) A community leader stated, “There used to be many forests and swamps here, but now almost everything has become oil palm plantations. The air feels hotter, and water dries up quickly.”

This statement reflects local perceptions of microclimate change and the loss of natural vegetation cover. These land-use changes have also resulted in soil degradation, marked by declining organic matter, increased compaction, and reduced infiltration capacity.

Such conditions contribute to higher surface runoff and a greater risk of seasonal flooding. Land-use intensification in tropical peat regions disrupts soil-water interactions and weakens natural hydrological regulation (Günsel et al., 2022). This is consistent with residents' complaints, such as *"Even with light rain, the drainage channels quickly overflow. Water no longer infiltrates like it used to."*

Another critical impact is the decline in biodiversity. The conversion of natural vegetation into oil palm monoculture eliminates wildlife habitats and disrupts ecological corridors. Oil palm expansion can reduce species richness by more than 50% compared to natural forests (Wagner et al., 2022). One respondent remarked, *"Animals like birds and monkeys are rarely seen now. They used to come near the gardens and even close to our homes."*

In addition, the use of fertilizers and herbicides contributes to water pollution, evidenced by increased sedimentation and nutrient concentrations in community waterways. Oil palm landscapes tend to have higher turbidity due to agrochemical runoff (Ran et al., 2023). A resident similarly stated, *"The water in the drainage channels is more turbid now. During the rainy season, the color changes, and it sometimes smells."*

The expansion of oil palm plantations has caused very real biodiversity loss and habitat fragmentation, as illustrated by the 2025 map: vegetation corridors that once linked habitat pockets are now severed by plantation blocks and access roads, reducing the ecological value of remaining forest and the ability of local species to migrate or maintain viable populations. Fragmentation further decreases ecosystem functions (water infiltration, flood buffering, and wildlife habitat), a consequence widely noted in monoculture expansion. For example, according to the International Council on Clean Transportation (ICCT) report, many new oil palm plantations replace tropical forests in Indonesia, including peatland rich in carbon, with severe consequences for biodiversity, climate, soil, and water quality (Irma et al., 2018).

Impacts on water quality are evident through patterns of contamination of community water sources: surface runoff from plantations carries nutrients (nitrate, phosphate) and pesticide residues into rivers and wells, thereby reducing water quality for domestic consumption and local irrigation (Asmara et al., 2024). A recent journalistic study of the Kais River watershed in Papua found that clearing forests for oil palm increased surface runoff by 21% and sediment yield by 16.9% in downstream communities, along with reported declines in water quality (Astari et al., 2025).

From a climate and fire-risk perspective, the drainage of peatlands and the creation of open drainage canals for plantation development elevate the

vulnerability to forest and land fires (*"karhutla"*), which in turn release large amounts of CO<sub>2</sub> and degrade regional air quality (Kartiwa et al., 2025). The water and soil disturbances resulting from converting peatlands into oil palm thus pose both immediate and long-term environmental threats. Social-environmental impacts (based on field interviews):

*"The well used to be clear and adequate, but now it looks cloudy and full of sediment after the rainy season."*

*"Areas where we used to gather rattan and small forest products are shrinking; our children lose these non-oil palm income sources."*

These quotes reflect reduced access to traditional natural resources and increased livelihood vulnerability, findings consistent with literature documenting the social impacts of oil palm expansion. Overall, the findings indicate that oil palm expansion has triggered substantial ecological degradation across soil, water, biodiversity, and climate regulation dimensions. The combination of scientific evidence and community experiences underscores the urgent need to strengthen environmental governance, enforce land-clearing regulations, and restore peatland and riparian ecosystems to ensure long-term sustainability in Tualang District.

#### *Propose Sustainable Management Strategies for Future Plantation Development*

Aligned with the environmental impacts identified in Tualang, sustainable management strategies must be formulated by balancing economic productivity with ecological conservation. First, the enforcement of sustainable palm oil certification, such as ISPO and RSPO, needs to be strengthened across the entire supply chain. The Indonesian government has expanded ISPO implementation through an upstream-downstream policy framework to ensure national sustainability (Sari, 2022). Capacity-building for smallholders is equally essential, as demonstrated by institutional training programs in Koto Tibun Village that enhance farmers' readiness to comply with ISPO standards (Haryanto et al., 2024).

Second, ecological conservation should be prioritized through the establishment of ecological buffer zones, wildlife corridors, and the protection of high-conservation-value areas (Nadhira et al., 2021). The HCSA (High Carbon Stock Approach) and HCV (High Conservation Value) frameworks adopted by RSPO are proven tools for identifying and safeguarding ecologically critical zones prior to plantation development. Third, community participation must be strengthened through sustainable landscape programs that empower local farmers to take an active role in ecological stewardship. Initiatives promoted by BKSDA show that community engagement improves

conservation awareness and reduces environmental conflict.

Fourth, innovative and environmentally friendly palm-oil waste management practices such as biogas production from palm residues, integrated agroforestry systems, and improved POME treatment are necessary to reduce pollution while increasing economic value (Powalla et al., 2021).

Finally, strict monitoring and regulatory enforcement in land clearing, especially in peatland ecosystems, are essential. Transparent monitoring systems involving third parties such as NGOs and local communities enhance accountability and help prevent further ecological degradation. This multi-stakeholder approach aligns with previous studies emphasizing governance as a central determinant of sustainable plantation development.

Beyond technological and regulatory measures, long-term sustainability of oil palm landscapes also depends on integrating circular-economy and landscape-based approaches that link waste management, biodiversity conservation, and community livelihoods. Recent studies demonstrate that converting palm-oil mill effluent (POME) and other residues into biogas and biofertiliser can significantly reduce greenhouse-gas emissions while generating renewable energy and lowering pollution loads in surrounding watersheds (Ramadhan et al., 2024). At the same time, the incorporation of oil-palm-based agroforestry and mixed-cropping systems has been shown to improve soil quality, enhance habitat connectivity, and increase farmers' income stability compared with monoculture plantations. These ecological and production-oriented innovations are most effective when supported by strong governance and transparent sustainability standards, which empirical evidence identifies as critical determinants of successful ISPO/RSPO implementation and environmental performance in Indonesia (Putri et al., 2022).

## Conclusion

The findings indicate that oil palm expansion between 2015 and 2025 has been the main driver of land-use change in Tualang District, particularly through the conversion of forests and peatlands. Spatial analysis shows that these changes have resulted in environmental degradation, including soil deterioration, biodiversity loss, increased runoff, and declining water quality, which are consistent with impacts perceived by local communities. In addition, land-use change has increased the vulnerability of settlements and reduced access to traditional natural resources. Based on these

findings, this study emphasizes the need for sustainable management strategies, including the protection of ecological buffer zones, strengthened implementation of ISPO/RSPO standards, improved regulatory enforcement, and community involvement in environmental monitoring. An integrated, landscape-based management approach is essential to ensure that oil palm development in Tualang District supports both environmental sustainability and community resilience.

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## Author Contributions

All authors contributed to writing this article.

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## Conflicts of Interest

No conflict interest.

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