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Spatial Analysis of Deforestation-Prone Zones Resulting from the Expansion of Patchouli Plantations and the Exploitation of Fuelwood for Distillation

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ABSTRACT

Deforestation in the inland regions of West Sulawesi has been increasing alongside the expansion of patchouli plantations and the high dependence of the patchouli oil distillation industry on fuelwood. This study aims to analyze changes in vegetation cover, identify the spatial distribution and hotspots of deforestation, and delineate deforestation-prone zones associated with patchouli plantation and distillation activities in Mamasa Regency. The analysis employed a spatial approach based on Geographic Information Systems (GIS), utilizing the Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 imagery for 2018 and 2025, vegetation change analysis (ΔNDVI), and Kernel Density Estimation (KDE) to identify deforestation hotspots. The results indicate that dense vegetation cover has experienced a significant reduction and spatial fragmentation, particularly in areas with high accessibility. Deforestation is concentrated in the central and eastern parts of Mamasa Regency and shows a strong spatial association with patchouli plantation and distillation locations. The highest deforestation intensity occurred during the 2021–2022 period, coinciding with increased patchouli oil prices that stimulated large-scale land clearing. High to very high deforestation-prone zones are generally located around patchouli distillation sites and areas subjected to intensive land use pressure. Based on IFAS and EFAS analyses, deforestation mitigation strategies should focus on transitioning to renewable energy, agroforestry-based commodity diversification, strengthening forest governance, and rehabilitating degraded areas to support sustainable forest management.

Keywords: deforestation, fuelwood, patchouli, SWOT analysis, West Sulawesi

INTRODUCTION

West Sulawesi is a key patchouli (Pogostemon cablin) production center in Indonesia, supplying the global essential oil market (Hidayatullah 2022). However, plantation expansion, often through forest conversion, has increased deforestation in the region (Chen *et al.* 2023). This forest loss, especially in upstream areas, has degraded hydrological functions, reducing infiltration and water retention while increasing flood and landslide risks in downstream areas like Mamuju (Kayitesi *et al.* 2022). Additionally, deforestation is further driven by fuelwood demand for patchouli oil distillation, leading to intensified forest exploitation (Mahlinda & Supardan 2020). Previous studies show that commodity-driven land use change is a major driver of tropical deforestation in Southeast Asia. In Indonesia, forest conversion closely follows commodity price cycles, as seen in oil palm and similarly in patchouli landscapes in West Sulawesi, where rising global demand accelerates smallholder clearing (Gaveau *et al.* 2022). Methodologically, NDVI from Sentinel-2 is widely used to monitor vegetation change, while KDE helps identify deforestation hotspots (Chouari 2024; Nowak *et al.* 2020). However, no study has yet integrated multi-date NDVI, KDE hotspot analysis, and the dual drivers of plantation expansion and fuelwood demand from distillation. Existing research either lacks spatial analysis of fuelwood impacts or does not quantify them. This study fills that gap by providing the first integrated spatial analysis of deforestation vulnerability in Mamasa Regency, combining ΔNDVI, KDE, and a multi-criteria GIS approach. Its novelty lies in linking deforestation hotspots to patchouli activity, identifying a peak event (2021–2022) driven by price shocks, and developing a vulnerability index that incorporates both ecological and socio-economic factors. Accordingly, the study analyzes land cover change, identifies deforestation-prone zones, and proposes mitigation strategies using GIS-based Multi-Criteria Evaluation and SWOT analysis.

METHODS

Study Area

This study was conducted in West Sulawesi Province, with a primary focus on Mamasa Regency. The regency was purposively selected due to its high intensity of patchouli cultivation and oil distillation

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activities, as well as its biophysical and socio-economic characteristics that reflect forest pressure in the inland areas of West Sulawesi. The tools and materials used can be seen in Table 1.

Data Collection Methods

This study employs a quantitative research approach, with data collection techniques consisting of field surveys and mapping. These methods were used to effectively obtain quantitative data across a large study area within a limited research timeframe (Nowak *et al.* 2020).

Research Procedures

This study was conducted in four stages: preliminary activities, data collection, analysis, and validation. The preliminary stage included research design, site surveys, literature review, and tool preparation. Data collection involved both secondary data, such as Sentinel-2 imagery for NDVI, DEMNAS for topography, and land use data from the Geospatial Information Agency, and primary data from interviews with farmers and local communities to assess plantation expansion and fuelwood use (Dewi *et al.* 2025). Data analysis was performed using GIS, with land cover change evaluated through NDVI derived from Sentinel-2 imagery (Sarif *et al.* 2023).

$$NDVI = (NIR - Red) / (NIR + Red)$$

Where low NDVI values indicate open or deforested land. NDVI values were compared across multiple periods (2015, 2020, and 2025) and overlaid with spatial variables such as road networks, settlement proximity, and patchouli plantation locations to identify deforestation drivers and delineate deforestation-prone zones. Deforestation mitigation strategies were formulated using a SWOT analysis based on spatial analysis results and socio-economic conditions (Bairwa *et al.* 2025).

RESULTS AND DISCUSSION

General Overview of the Study Area

The study was conducted in West Sulawesi Province (±16,787 km²), which consists of six regencies with diverse landscapes from coastal to mountainous areas. Its complex topography and high rainfall support extensive forests, while the economy relies on agriculture, plantations, and forestry, with patchouli as a key commodity. Mamasa Regency was selected due to its mountainous terrain, strong community dependence on forest resources, and the expansion of patchouli cultivation and fuelwood-based distillation, which increases pressure on forests (Sarif *et al.* 2023).

Vegetation Density Index (NDVI)

Vegetation density in Mamasa Regency was analyzed using the Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 imagery from 2018 and 2025.

- Vegetation Density (NDVI) in 2018
  The 2018 NDVI map (Figure 1) shows that Mamasa Regency was dominated by dense vegetation, mainly in the western, southwestern, and central areas, indicating well-preserved forest cover in hilly and mountainous regions. Moderate vegetation occurred in transitional zones between forests and smallholder agriculture, while sparse vegetation was limited to areas around settlements, roads, and localized land conversion. Overall, forest pressure in 2018 remained localized and had not yet resulted in widespread degradation.
- Vegetation Density (NDVI) in 2025
  The 2025 NDVI analysis (Figure 2) shows a notable increase in areas with low and moderate vegetation density, particularly in the central, eastern, and southeastern parts of Mamasa Regency. Although

Table 1 Tools and materials

Tools and materials	Function
Field equipment :	
a. Camera	To capture images (documentation)
b. GPS	To determine the observation location
c. Drone	For aerial observation
Laboratory equipment :	
a. Personal Computer	For data input and processing
b. Software ArcGis	For image data processing
Research materials :	
a. DEMNAS	For elevation and slope values
b. Citra Sentinel-2	For forest vegetation observation
c. Land Use	To identify land use at the study site
d. Stationery	For data recording
e. Questionnaire	Supporting Data

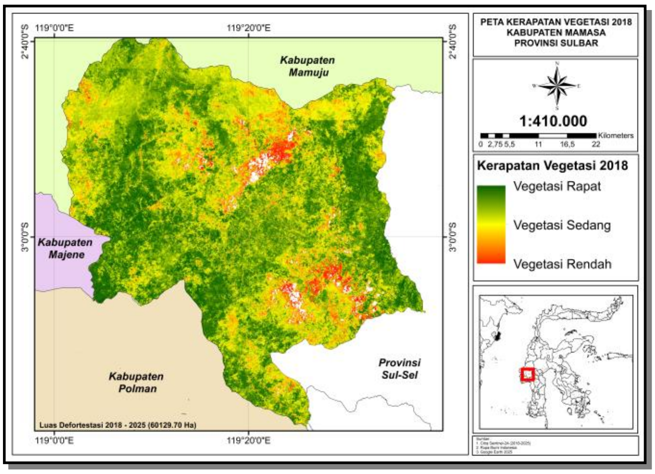

Figure 1 Vegetation density map in 2018.

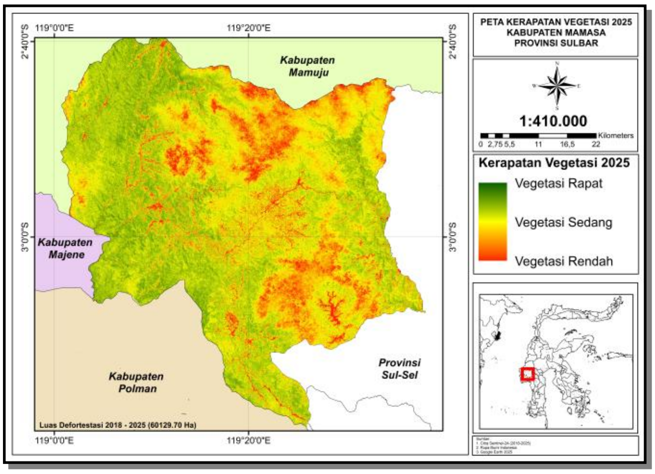

Figure 2 NDVI-based vegetation density map in 2025.

dense vegetation remained, its extent decreased and became more fragmented, mainly persisting in steep and less accessible areas. In contrast, areas with higher accessibility experienced greater land use pressure, with low vegetation density forming more continuous patterns along road networks and valley areas, indicating ongoing and widespread land conversion.

The pattern of fragmentation and accessibility-driven vegetation loss observed in this study is consistent with findings from other tropical plantation landscapes. Chouari (2024) documented comparable NDVI-based vegetation decline in areas experiencing agricultural encroachment, where loss of dense canopy was concentrated along road corridors and valley bottoms due to ease of access. Similarly, Haeruddin *et al.* (2023), analyzing multi-temporal Sentinel-2A imagery in Sulawesi, found that vegetation index decline was most pronounced in areas adjacent to existing settlements and infrastructure. These patterns collectively indicate that accessibility is a primary spatial predictor of deforestation initiation in tropical upland landscapes, a finding further supported by the spatial correspondence between road networks and NDVI decline observed in the present study.

Spatial Distribution of Deforestation (2018–2025)

The spatial distribution of deforestation in Mamasa Regency was analyzed using changes in the Normalized Difference Vegetation Index (ΔNDVI) for the 2018–2025 period as an indicator of vegetation change, where decreasing NDVI values represent forest degradation and land conversion. ΔNDVI values were classified into five categories: very high decrease (≤ −0.50), high decrease (−0.50 to −0.20), stable (−0.20 to +0.20), high increase (+0.20 to +0.50), and very high increase (> +0.50).

Based on the deforestation distribution map (Figure 3), most of Mamasa Regency is characterized by areas experiencing high to very high vegetation decline, forming clustered hotspots mainly in the central, eastern, and southern regions. These zones are generally located in areas with higher accessibility, making them more vulnerable to agricultural and plantation expansion. In contrast, areas with stable or increasing vegetation are predominantly found in steep

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and less accessible terrain, where natural constraints limit land clearing and reduce deforestation intensity.

- Relationship Between Deforestation and Patchouli Plantation Locations
  The deforestation analysis was integrated with field-mapped patchouli plantation locations, identifying 60 plantation sites in Mamasa Regency (Figure 3). Although representing only accessible sites, the overlay analysis shows that most plantations are located within zones of high to very high vegetation decline. This spatial pattern indicates a strong association between patchouli cultivation activities and vegetation loss, occurring through both direct forest conversion and degradation in transitional areas, as reflected by the ΔNDVI analysis.
- Relationship Between Deforestation and Patchouli Distillation Locations
  This study also mapped 24 patchouli oil distillation sites based on field observations (Figure 3), representing the minimum observable distribution during the study period. Spatial analysis shows that most distillation sites are located near zones of high to very high vegetation decline, indicating additional pressure on surrounding vegetation, particularly due to fuelwood demand. Although impact intensity varies spatially, patchouli distillation functions as a local driver that reinforces vegetation degradation processes.
- Temporal Context of the Spatial Distribution of Deforestation
  The ΔNDVI map shows cumulative vegetation change during 2018–2025, with peak deforestation occurring in 2021–2022, reaching 210,707.75 ha (Table 2). Field observations and stakeholder interviews indicate that this period coincided with a sharp increase in patchouli oil prices, which drove rapid expansion of patchouli cultivation and increased fuelwood demand for distillation. Land clearing involved both forest conversion and the removal of existing vegetation, including cocoa trees used as fuelwood prior to plantation establishment.

The concentration of peak deforestation in the 2021–2022 price-driven period mirrors patterns observed in commodity-driven deforestation studies. Gaveau *et al.* (2022) showed that deforestation in Indonesia's oil palm sector closely follows price cycles, with clearing increasing during high prices and declining when prices fall—similar to the patchouli-driven pattern in this study. This price-elastic response is especially strong in smallholder systems, where land expansion decisions are rapid and less regulated (Guye *et al.* 2026). The sharp decline in deforestation after 2022 (to 107.15 ha in 2022–2023 and 24.17 ha in 2023–2024) supports this interpretation, as falling patchouli prices reduced incentives for further clearing. Unlike large-scale plantations with longer investment cycles, this pattern reflects the short-term, price-triggered deforestation typical of smallholder rubber and cocoa frontiers in tropical Asia (Chen *et al.* 2023). In subsequent periods, deforestation extent declined in response to falling patchouli prices, land constraints, and reduced distillation intensity. Nevertheless,

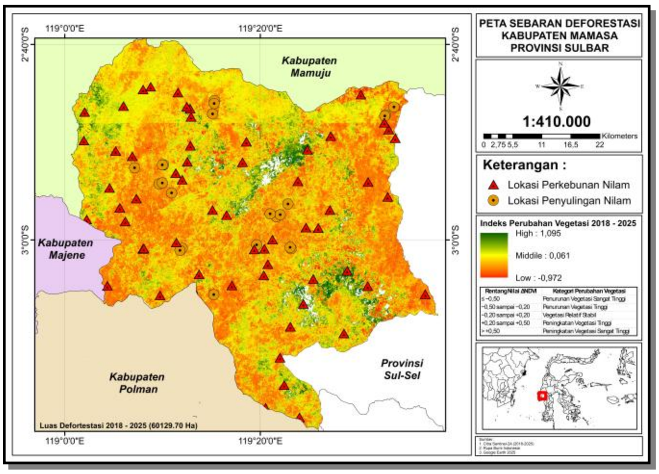

Figure 3 Spatial distribution of deforestation (2018–2025).

Table 2 Deforestation area by period (2018–2025)

Year	Deforestation Area (ha)
2018–2019	289.88
2019–2020	5975.06
2020–2021	5795.62
2021–2022	210705.75
2022–2023	107.15
2023–2024	24.17
2024–2025	315.57

localized deforestation persisted until 2024–2025, as reflected by continued areas of high NDVI decline.

Identification of Deforestation Hotspots

Deforestation hotspots in Mamasa Regency were identified using Kernel Density Estimation (KDE) applied to ΔNDVI-derived vegetation change data for the 2018–2025 period. This approach was used to map the spatial concentration of deforestation events and distinguish high-intensity areas from more dispersed occurrences. KDE results were classified into five hotspot categories—very low, low, moderate, high, and very high—where higher values indicate more intensive and recurrent vegetation decline.

The KDE-based deforestation hotspot map (Figure 4) shows that deforestation in Mamasa Regency is spatially uneven, forming distinct concentration zones. High to very high hotspots are mainly located in the eastern and parts of the central regions, indicating greater deforestation intensity in these areas. In contrast, most of the regency falls within low to very low hotspot categories, suggesting that deforestation is generally dispersed but concentrated in specific high-pressure locations, reflecting a heterogeneous deforestation pattern.

The KDE analysis shows deforestation density values ranging from 0.00165 to 0.15953, classified into five hotspot categories from very low to very high (Table 3). Low categories indicate sporadic deforestation, while moderate hotspots represent transitional areas with emerging clustering. High to very high hotspots form distinct spatial clusters, reflecting persistent land use pressure, particularly in more accessible areas. The use of KDE to characterize deforestation hotspot intensity in this study is methodologically consistent with approaches applied in tropical deforestation monitoring literature. In the context of Indonesian forests, the spatially heterogeneous deforestation pattern revealed by KDE with high-intensity clusters in accessible zones and dispersed low-intensity events elsewhere—aligns with deforestation profiles documented by Mutolib *et al.* (2019) for Sulawesi, where the dominant deforestation pattern was characterized as spatially scattered but with distinct cluster formation in areas adjacent to agricultural frontiers. The KDE density range (0.00165–0.15953) obtained in this study reflects moderate-to-high spatial clustering of deforestation events, consistent with the pattern expected in smallholder-dominated plantation landscapes where clearing decisions occur independently but are spatially anchored by proximity to existing farms, roads, and distillation sites. This contrasts with large-scale industrial deforestation, which typically produces more uniform and contiguous clearing patterns detectable as single large patches rather than density gradients (Gaveau *et al.* 2022).

Deforestation-Prone Zones

Deforestation-prone zones in Mamasa Regency (Figure 5) were identified using a vulnerability index integrating vegetation change (ΔNDVI), deforestation hotspot density, and proximity to land use activities,

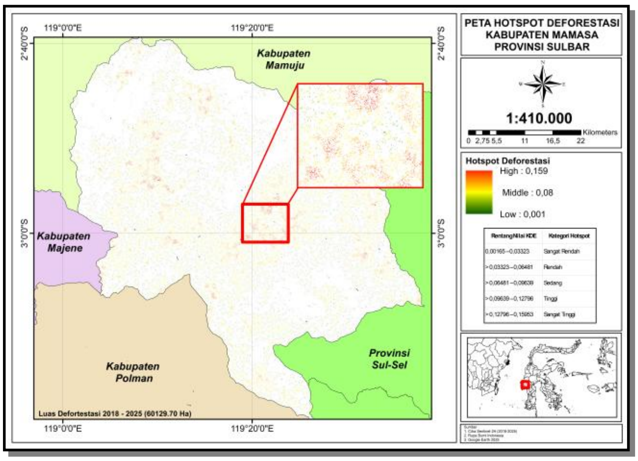

Figure 4 Deforestation hotspot patterns.

Table 3 Hotspot categories

Class	KDE value range	Hotspot categories	Meaning / Interpretation
1	0,00165–0,03323	Very low	Very low deforestation density, with events occurring sporadically and not forming clusters
2	>0,03323–0,06481	Low	Low deforestation density, with the emergence of small but not yet significant clusters.
3	>0,06481–0,09639	Moderate	Moderate deforestation density, indicating transitional areas with potential hotspot formation.
4	>0,09639–0,12796	High	High deforestation density, forming distinct clusters and requiring management attention.

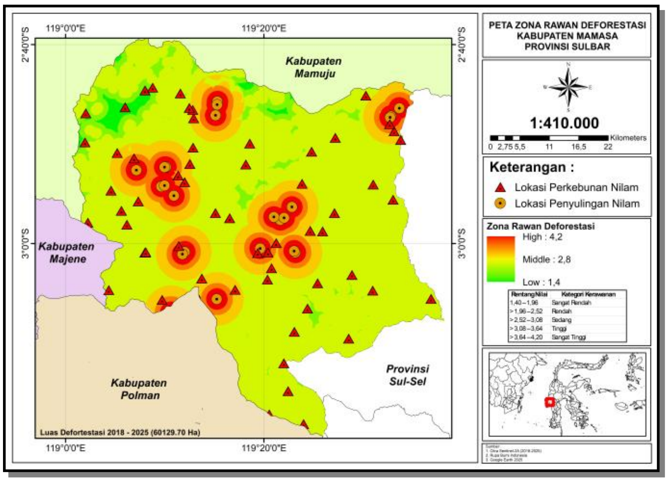

Figure 5 Deforestation-prone zones.

particularly patchouli plantations and distillation sites. The relative index ranged from 1.40 to 4.20 and was classified into five vulnerability levels. Low-vulnerability zones are generally located in areas distant from human activities with minimal vegetation change, while moderate-vulnerability zones represent transitional areas associated with emerging patchouli cultivation. High to very high vulnerability zones form distinct clusters, predominantly surrounding patchouli distillation sites, indicating concentrated deforestation pressure driven by fuelwood demand and plantation expansion.

The spatial clustering of high-vulnerability zones around distillation sites and accessible plantation areas is consistent with findings from deforestation vulnerability assessments in other smallholder commodity landscapes in Indonesia. Dewi *et al.* (2025) demonstrated that in peatland-adjacent plantation areas of Central Kalimantan, proximity to processing facilities (analogous to distillation sites) was a significant predictor of land conversion intensity in multi-criteria vulnerability mapping. Bairwa *et al.* (2025), applying land change modeling in tropical agricultural contexts, similarly found that areas within the influence zones of processing infrastructure consistently ranked among the highest deforestation-prone classes in vulnerability indices. The vulnerability index range (1.40–4.20) derived in this study thus reflects a gradient from minimally threatened steep terrain to highly threatened accessible lowlands and valley systems, a pattern structurally consistent with deforestation vulnerability gradients documented for upland tropical commodities elsewhere in Sulawesi and Kalimantan (Arifanti *et al.* 2022).

The strong spatial correspondence between high-vulnerability zones, deforestation hotspots, and patchouli-related activities highlights the significant role of the patchouli sector in shaping deforestation dynamics in Mamasa Regency, particularly in accessible areas.

Deforestation Mitigation Strategies

Deforestation mitigation strategies were prioritized using an Internal Factors Analysis Summary (IFAS) and an External Factors Analysis Summary (EFAS) to evaluate regional strengths, weaknesses, opportunities, and threats (Arifanti *et al.* 2022). IFAS highlighted internal conditions such as renewable energy potential and high dependence on fuelwood in patchouli oil distillation, while EFAS captured external drivers including sustainability support, development pressure related to Indonesia's new capital city (IKN), commodity price fluctuations, and disaster risks.

The analysis indicates that effective deforestation mitigation in West Sulawesi requires integrated SO, WO, ST, and WT strategies. Key priorities include transitioning patchouli oil distillation from fuelwood to renewable energy sources (e.g., biogas and solar), promoting agroforestry and alternative high-value crops on sloping land, and strengthening forest governance through incentives, certification of environmentally friendly patchouli oil, and enhanced monitoring. Additional measures involve aligning regional development with IKN through sustainable resource supply, implementing moratoria on land clearing in disaster-prone areas, and rehabilitating degraded forests.

Collectively, these strategies aim to reduce deforestation pressure, mitigate hydrometeorological risks, and sustain local livelihoods.

CONCLUSION

The results of this study indicate that deforestation in Mamasa Regency increased during the 2018–2025 period, with spatial patterns concentrated in areas with high accessibility. NDVI, ΔNDVI, and deforestation hotspot analyses reveal a strong relationship between vegetation cover decline and the expansion of patchouli plantations and distillation activities, particularly due to fuelwood demand. Zones with high to very high deforestation vulnerability are generally concentrated around distillation sites and areas experiencing intensive land use pressure. Based on the IFAS–EFAS analysis, deforestation mitigation requires an integrated strategy involving a transition to renewable energy, agroforestry-based commodity diversification, strengthened forest governance, and the rehabilitation of degraded areas to reduce pressure on forests while sustaining local livelihoods.

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