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Spatial Dynamics of Vegetation Index Changes in the Weda Nickel Mining Area, Halmahera Island, Indonesia

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Abstract. *Nickel mining in Weda, Halmahera Island, is one of the largest nickel mines in Indonesia, and its activities impact changes in vegetation indices and cover in the area. The research uses Landsat 8 satellite imagery from 2019, 2022, and 2025 with the NDVI algorithm to analyse changes in vegetation index values and vegetation cover. The research results show that the NDVI values for 2019 are the lowest at -0.233774 and the highest at 0.999903; for 2022, the lowest is -0.369486 and the highest is 0.799867; and for 2025, the lowest is -0.369486 and the highest is 0.530372. The NDVI values were then classified into 4 vegetation cover classes: active mining areas, sparse, moderate, and dense vegetation. The active mining area in 2019 was 1.27 km², in 2022 it was 11.91 km², and in 2025 it was 18.20 km². Sparse vegetation in 2019 covered 5.73 km², in 2022 it covered 6.03 km², and in 2025 it covered 8.07 km². Moderate vegetation in 2019 covered 5.72 km², in 2022 it covered 2.68 km², and in 2025 it covered 2.21 km². Dense vegetation in 2019 covered 522.64 km², in 2022 it covered 515.35 km², and in 2025 it covered 507.20 km². The presentation of the mining area continues to increase every year. The results of this research are expected to be used for continuous monitoring to ensure compliance with environmental standards and support rehabilitation programmes in Weda and other tropical mining areas.*

Keywords: *NDVI; Nickel Mining; Spatial Dynamics; Vegetation Cover; Weda*

1. Introduction

Nickel mining, as one of the key mineral commodities in the global energy transition toward electric vehicles and renewable energy, is experiencing a significant increase in demand. Indonesia, as the world's largest nickel producer, plays a central role in this global supply chain (Zou et al., 2025). However, this massive expansion of extractive activities often clashes with environmental protection, especially in sensitive ecosystems like tropical forests (Nasution et al., 2024). The environmental impacts it causes, including deforestation, erosion, and pollution, have become a serious concern at both global and national levels (Lo et al., 2024). This issue points out the need for careful monitoring and analysis of environmental changes, particularly in vegetation cover, as a key indicator of ecosystem health (Wahyono et al., 2024).

Halmahera Island, in North Maluku province, is one of the areas most affected by the expansion of nickel mining in Indonesia (Heijlen & Duhayon, 2024). Specifically in the Weda area, the operation of a large-scale nickel industrial complex has led to drastic changes in land use. Primary forests rich in biodiversity have been converted into mining areas and their supporting facilities, resulting in the loss of natural habitats and threats to endemic species. These changes not only impact terrestrial ecosystems but also trigger erosion and sedimentation that threaten marine ecosystems, including vulnerable coral reefs. Recent

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reports indicate that vegetation cover continues to decline significantly as mining areas expand (Nasution et al., 2024).

To monitor and measure the rapid and widespread impact of environmental change, remote sensing technology offers an efficient solution (Rifai et al., 2025). Vegetation indices, such as the Normalised Difference Vegetation Index (NDVI), have been widely recognised as effective tools for quantifying vegetation cover and health (Sun et al., 2024). By analysing changes in NDVI values from multi-temporal satellite data, we can track vegetation degradation and recovery over time (Hutayanon & Somprasong, 2023). Similar studies in other mining areas in Indonesia, such as in Southeast Sulawesi, have successfully identified patterns of vegetation cover change caused by mining activities (Adidharma et al., 2023). However, specific and detailed analysis of the spatial dynamics of vegetation change in Weda is still limited.

Although the general impacts of nickel mining have been documented, understanding the spatial dynamics of vegetation change specifically in the Weda mining area is still not comprehensive. Most research focuses on regional scales or general land cover changes, without delving into the temporal and spatial variations of the vegetation index itself. Spatial dynamics analysis allows us to identify areas most vulnerable to degradation, understand its spread patterns from the mine core, and evaluate the effectiveness of mitigation or reclamation efforts (Thakur et al., 2025). This knowledge is crucial for formulating more targeted and sustainable environmental policies.

Therefore, this study aims to analyse the spatial dynamics of vegetation index changes in the Weda nickel mining area, Halmahera Island, from 2019 to the present. Using multi-temporal remote sensing data and spatial analysis methods, this study will quantify the rate and pattern of vegetation cover change. This research is expected to make a significant contribution to the scientific literature on the impact of mining on sensitive tropical ecosystems. Practically, these findings will be relevant for policymakers, mining companies, and environmental agencies in designing more effective mitigation and rehabilitation strategies. Furthermore, the generated spatial data can be used to monitor companies' compliance with environmental standards and support sustainable natural resource management initiatives.

2. Methods

This research was conducted in the nickel mining area of Weda, Halmahera Island, North Maluku Province, Indonesia. The area of the mining area is 535.67 km^2. The research location can be seen in Figure 1. The vegetation index values used are the result of image processing with the Normalised Difference Vegetation Index (NDVI) transformation. NDVI is a mathematical approximation based on the reflection (albedo) of vegetation canopies, which can be a ratio or a combination of visible and near-infrared radiation (Hutayanon & Somprasong, 2025).

Essentially, NDVI is used to determine the greenness level of leaves, with near-infrared wavelengths being excellent for this purpose, serving as the starting point for dividing vegetation areas (Hutayanon & Somprasong, 2025). Because the optical properties of chlorophyll are very distinctive, namely that chlorophyll absorbs the red spectrum and strongly reflects the infrared spectrum. For Landsat 8 OLI/TIRS, to determine the NDVI value, band 4 (red) and band 5 (near infrared) are used (Lasaponara et al., 2022). The NDVI values were then classified into 4 classes based on Table 1.

$$NDVI = (NIR - RED)/(NIR + RED) \quad (1)$$

Description: NIR = Near-infrared channel (band 5 on Landsat 8 with a wavelength of 0.85-0.88 µm). RED = Red channel (band 4 on Landsat 8 with a wavelength of 0.64-0.67 µm).

Table 1. Classification of NDVI values for vegetation cover

NDVI Class	NDVI Value Range	Description Vegetation Cover
Very low	< 0,15	Active mining area or critical land, without vegetation
Low	0,15 – 0,25	Sparse vegetation, disturbed areas, or mining processes
Medium	0,26 – 0,35	Moderate vegetation
High	> 0,35	Dense vegetation, Forest area

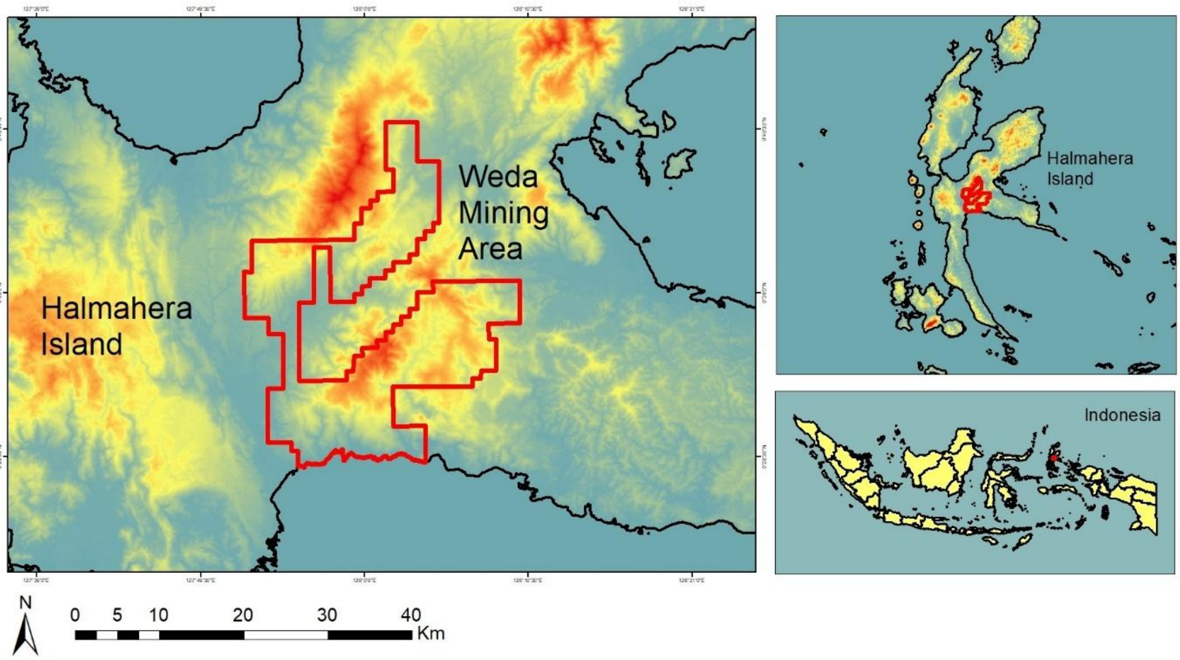

Figure 1. Research Location: Nickel Mining Area, Weda, Halmahera Island, Indonesia

NDVI values range from -1.0 to +1.0 (Li et al., 2025). Values greater than 0.1 indicate an increase in the greenness and intensity of vegetation (Li et al., 2025). Values between 0 and 0.1 are generally characteristic of rocks and bare land, while values less than 0 indicate clouds, ice, and snow. The vegetation surface has an NDVI value range of 0.1 for grasslands and shrublands to 0.8 for tropical rainforest areas (Lasaponara et al., 2022). On non-vegetated land, including human settlements, water bodies, open bare ground, and areas with damaged vegetation, the ratio will not be high (minimum), while in areas with very dense vegetation, the ratio between the brightness levels of the red light channel and the near-infrared light channel will be very high (Li et al., 2025).

3. Results and Discussion

3.1 NDVI values for the years 2019, 2022, and 2025

The NDVI analysis results show that the highest NDVI value in 2019 was 0.999903, indicating very dense and healthy vegetation. Conversely, a low or negative value of -0.233774 indicates areas with little or no vegetation, active mining areas, or critical land. In 2022, the lowest NDVI value was -0.530372, indicating an increase in the area of mining, and the highest NDVI value was 0.799867, indicating a decrease in the area with high vegetation. In 2025, the lowest vegetation index in 2025 continued to increase with an NDVI value of -0.369486, while the highest value continued to decrease to 0.530372. The visualisation of the NDVI values map can be seen in Figure 2.

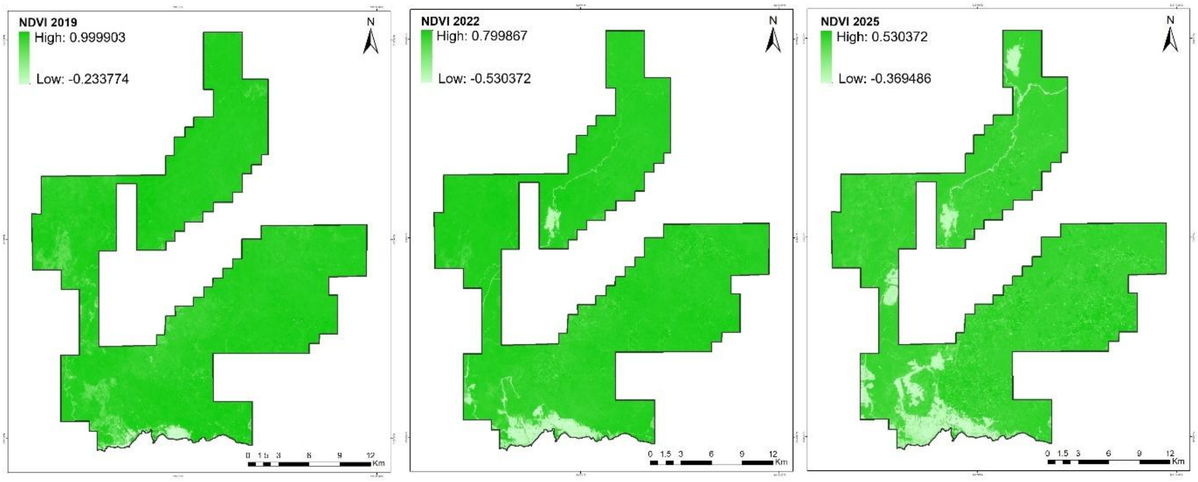

Figure 2. NDVI Value Map of Nickel Mining Area in Weda, Indonesia

3.2 Vegetation cover in 2019, 2022, and 2025

Based on the NDVI values in Table 1, the NDVI values were then classified into 4 classes: active mining area, sparse vegetation, moderate vegetation, and dense vegetation. In 2019, the vegetation cover type of the Active Mining Area had an area of 1.27 km² (0.24%), which increased to 11.91 km² (2.22%) in 2022 and further expanded to 18.20 km² (3.40%) by 2025. This increase indicates intensive mining area expansion and aligns with the findings of various international studies regarding increased mining activity and deforestation in surrounding areas, as seen in mining in China and other tropical regions. A study by Jiang et al., (2022) confirms that monitoring NDVI can effectively detect mining land expansion and changes in vegetation cover due to human activities.

Table 2. Vegetation cover area (km²)

Cover Type	Cover Area (km²)		
	2019	**2022**	**2025**
Active mining area	1.27	11.91	18.20
Sparse vegetation	6.03	5.73	8.07
Moderate vegetation	5.72	2.68	2.21
Dense vegetation	522.64	515.35	507.20
Total area	535.67		

The area of sparse vegetation cover in 2019 was 6.03 km² (1.13%), slightly decreasing to 5.73 km² (1.07%) in 2022, but increasing to 8.07 km² (1.51%) in 2025. This fluctuation reflects the direct and indirect impacts of mining activities, as well as the possibility of less effective or slow revegetation stages on former mining land.

The study by Hutayanon & Somprasong, (2025) on mining areas in Southeast Asia showed a similar pattern, where sparsely vegetated areas often increased after mining disturbance before comprehensive restoration processes were implemented. The total vegetation cover area is presented in Tables 2 and 3 and Figure 4. The area of moderate vegetation cover decreased from 5.72 km² (1.07%) in 2019, drastically reducing to 2.68 km² (0.50%) in 2022, and further shrinking to 2.21 km² (0.41%) in 2025. The percentage of vegetation cover area can be seen in Tables 2 and 3. The vegetation cover in this study can be seen in Figure 3.

Table 3. Percentage of Vegetation Cover Area (%)

Cover Type	Cover Area (%)		
	2019	2022	2025
Active mining area	0.24	2.22	3.40
Sparse vegetation	1.13	1.07	1.51
Moderate vegetation	1.07	0.50	0.41
Dense vegetation	97.57	96.21	94.69
Total area	100		

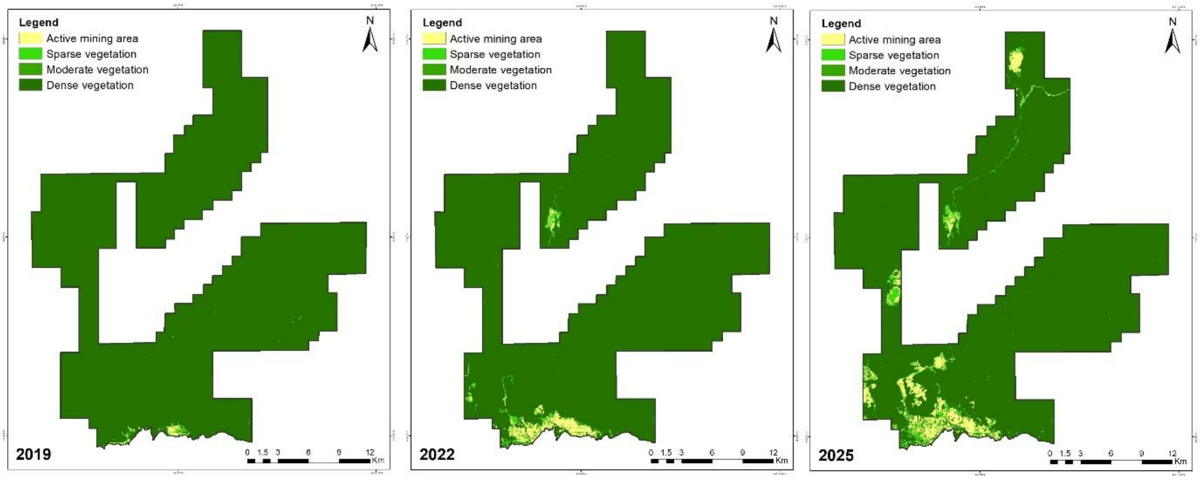

Figure 3. Vegetation cover in 2019, 2022 and 2025

This decline indicates a gradual degradation of habitat due to fragmentation and the conversion of forest land into mining areas and other environmental pressures. Studies on mineral mining in various locations show that mid-level vegetation is generally most affected by increased mining activity and land use change (Zhou & Zhang, 2025). The area of dense vegetation cover is the largest throughout the period, but it is decreasing: 522.64 km² (97.57%) in 2019, decreasing to 515.35 km² (96.21%) in 2022, and 507.20 km² (94.69%) in 2025. The decrease in dense vegetation cover area is a key indicator of the decline in the quality of tropical forest ecosystems, which impacts biodiversity loss and increases the risk of flooding, erosion, and local climate change. The studies by Guo et al., (2023) and Hutayanon & Somprasong, (2025) also found a pattern that areas with dense vegetation are most vulnerable to deforestation due to intensive mining.

3.3 Changes in vegetation cover in 2019, 2022, and 2025

The changes in vegetation cover in the Weda nickel mining area, Halmahera, Indonesia, between 2019 and 2025 illustrate spatial dynamics that reflect the significant impact of mining activities on the local ecosystem. The four vegetation cover classes analysed were active mining area, sparse vegetation, moderate vegetation, and dense vegetation, each showing different patterns of change over time.

During the period 2019-2022, the area of active mining areas increased by 10.64 km², and continued to grow by another 6.29 km² during the period 2022-2025. This indicates aggressive and sustainable mining expansion, leading to the conversion of vegetated land into active mining areas. This phenomenon is consistent with the findings of Rakuasa et al., (2025), study on nickel mining areas in Obi Island, which also showed an increase in mining land area with a drastic loss of vegetation cover, leading to habitat fragmentation and ecological degradation. A global study by Mervine et al., (2025) also showed that nickel mining in tropical regions like Indonesia places high pressure on vegetation with significant biomass carbon. Changes in vegetation cover for the periods 2019-2022 and 2022-2025 can be seen in Table 4 and Figure 4.

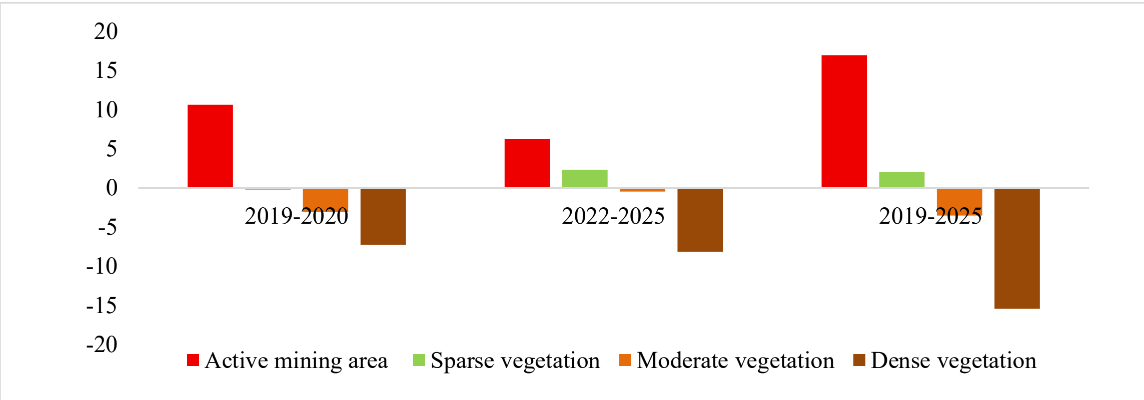

Figure 4. Changes in vegetation cover in 2019, 2022, and 2025

Table 4. Vegetation cover change for the periods 2019-2022 and 2022-2025 in km2

Cover Type	Period (km²)	
	2019-2022	2022-2025
Active mining area	10.64	6.29
Sparse vegetation	-0.3	2.34
Moderate vegetation	-3.04	-0.47
Dense vegetation	-7.29	-8.15

Sparse vegetation experienced a decrease in area of 0.3 km² during the period 2019-2022 but then significantly increased by 2.34 km² during the period 2022-2025. This pattern indicates the possible presence of non-optimal revegetation processes occurring in parts of the former mining area or at the edges of the mining area that are partially regenerating but have not yet returned to denser vegetation conditions. The initial decline in sparse vegetation aligns with the direct disturbance from mining activity, while the subsequent increase suggests limited potential for vegetation recovery and requires environmental management attention.

Moderate vegetation consistently shows a decreasing trend in area, specifically -3.04 km² during the 2019-2022 period, and continues to decrease by -0.47 km² during the 2022-2025 period. This indicates further degradation at the intermediate vegetation level, which can be interpreted as a transition zone between the mining area and dense forest (Adeoye, 2016). This degradation is typically a result of ecological threshold pressures from land clearing and mining activities, leading to habitat fragmentation and declining ecosystem function (Thakur et al., 2025). Similar studies in tropical areas and other mineral mines show that moderate vegetation cover is most vulnerable to shrinkage due to sustainable mining activities.

3.4 Changes in the area of nickel mining

Dense vegetation, which is the most extensive vegetation cover, also experienced a significant decrease of -7.29 km² during the 2019-2022 period and was further reduced by -8.15 km² during the 2022-2025 period (Figure 6 and 6). This decline reflects a decrease in the quality and quantity of dense forest ecosystems, which impacts reduced biodiversity, increased erosion and flood risks, and disruptions to carbon function and local climate. A study by Rakuasa et al., (2025), also confirms the close relationship between forest cover loss and the increased risk of flooding in the Weda Bay area due to deforestation triggered by nickel mining expansion. The decline in dense forest cover aligns with other international findings that examine the impact of mining on tropical habitats.

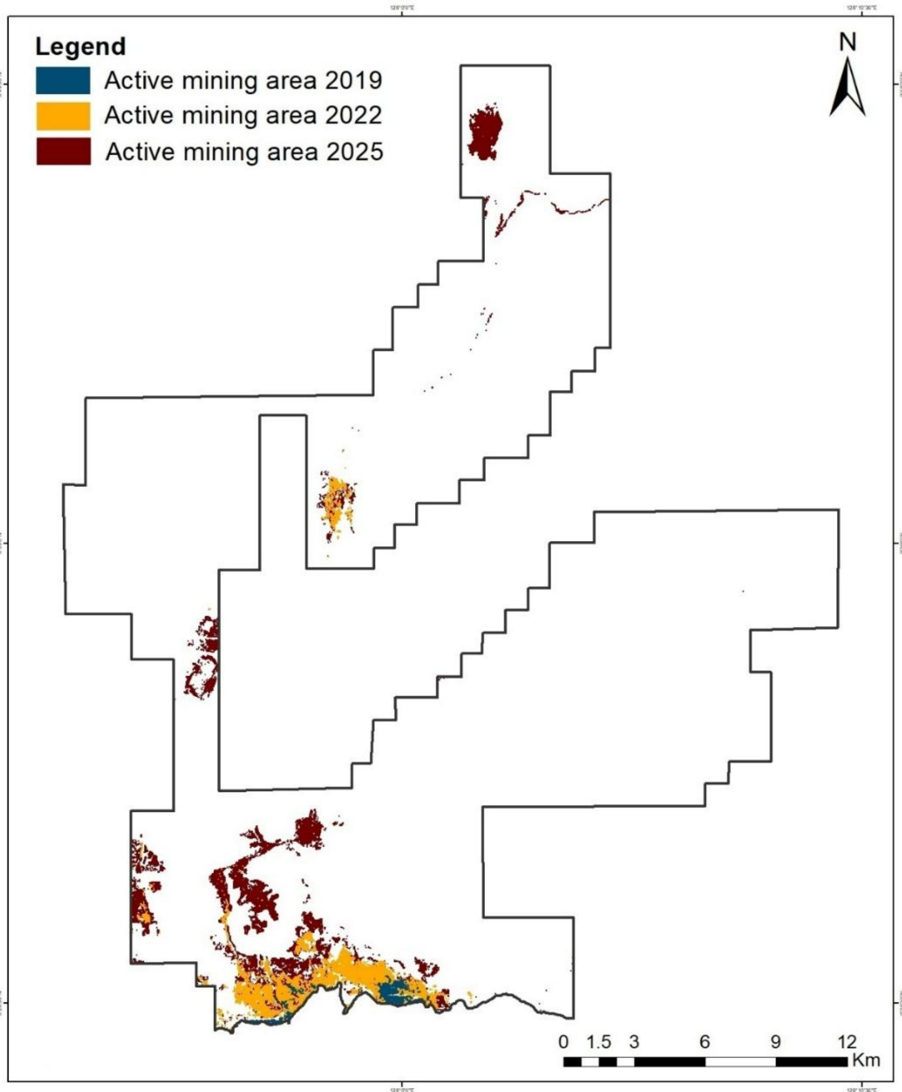

Figure 6. Development of mining areas in 2019, 2022, and 2025

Changes in the nickel mining sectorThe change in the area of nickel mining in Weda, Halmahera Island, between 2019 and 2025 shows very significant development. The area of active mining increased from 1.27 km² in 2019 to 11.91 km² in 2022 and continued to expand to 18.20 km² in 2025. This rapid growth reflects the expansion of the nickel mining industry in the Weda Bay area, one of the world's largest nickel mining and processing projects, involving global partnerships such as PT Weda Bay Nickel, Tsingshan Holding Group, Eramet, and PT Antam (Lo et al., 2024).

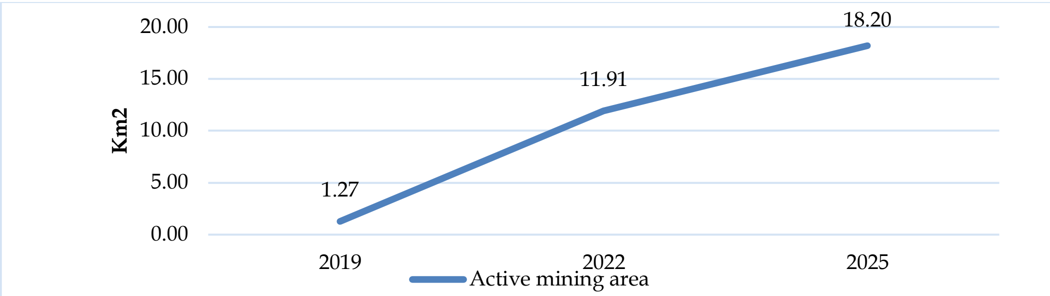

Figure 5. Trend of increasing mining area in 2019, 2022, and 2025

This mining area expansion is primarily driven by increasing global demand for nickel as a key component of electric vehicle batteries and stainless steel. The rapidly growing electric vehicle industry is driving up the need for high-quality nickel raw materials, making mining in Halmahera one of the strategic centres of global nickel production. This condition increases pressure on land in the area, accelerating the process of deforestation and converting natural land into active mining areas (Wahyono et al., 2024).

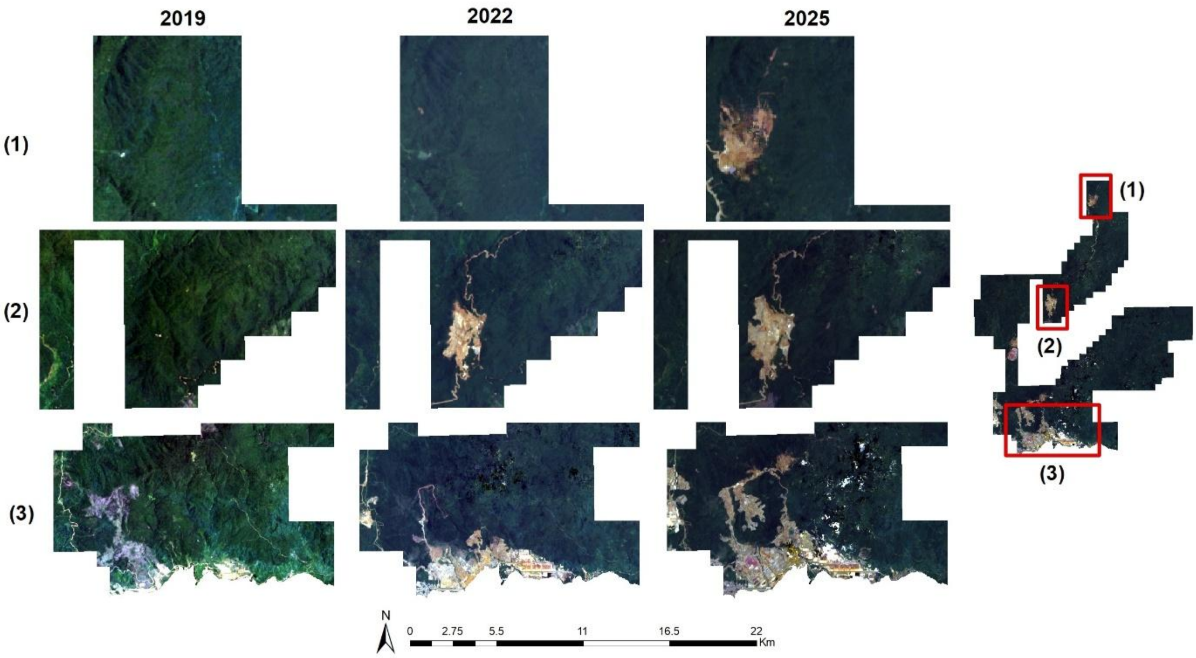

Figure 7. The transformation of mining area expansion can be seen in Landsat imagery

Additionally, despite PT Weda Bay Nickel implementing some sustainability standards and land rehabilitation programmes, the high rate of mine area expansion poses significant challenges for environmental management. Mitigation and rehabilitation efforts must continue to be monitored and strengthened to minimise the negative impact on the ecosystem. There is an urgent need for a remote sensing and sustainable environmental monitoring approach to ensure the long-term preservation of local ecosystems (Listyono & Manurung, 2025).

The social impact of expanding the mining area is also no less important. Changes in land use open up economic opportunities in the form of jobs and infrastructure, but on the other hand, they lead to social conflicts related to land use and a decline in the quality of life for local communities due to environmental pollution and disruption to water resources. Studies by JATAM and reports from local communities emphasise that rapid mining must align with inclusive social policies and community involvement in decision-making to minimise conflict (Nasution et al., 2024). The transformation of mining area expansion can be seen in the Landsat image in Figure 7.

In conclusion, the change in the area of nickel mining in Weda from 2019 to 2025 shows rapid industrial expansion with complex ecological and social impacts. Sustainable management, impact mitigation, and the integration of socio-ecological policies are key to guiding responsible mining development, ensuring a balance between economic needs and environmental conservation in this resource-rich Halmahera region.

Conclusions

This study shows that the expansion of nickel mining in the Weda area, Halmahera, from 2019 to 2025 leads to a significant decrease in dense and moderate vegetation cover and an increase in active mining areas, indicating the degradation of sensitive tropical ecosystems and habitat fragmentation. Multi-temporal NDVI analysis has proven effective in monitoring the spatial dynamics of vegetation change, thus providing important data for environmental management. Therefore, it is crucial to implement strict mitigation strategies, including post-mining land reclamation based on native vegetation, sustainable environmental monitoring using remote sensing technology, and involving local communities in decision-making. This integrative and sustainable policy can maintain a balance between economic growth through mining and the conservation of natural resources for environmental and social sustainability in the Halmahera region.

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Conflicts of Interest

The authors declare no conflict of interest.

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