Land Cover Change Dynamics As an Indicator of Deforestation Rate in Gunung Leuser National Park

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Abstract.

Gunung Leuser National Park (GLNP) is one of the most important conservation areas in Indonesia, serving as a habitat for various rare and protected species such as the Sumatran tiger, elephant, rhinoceros, and orangutan. Nevertheless, this area faces serious threats from deforestation caused by human activities, including illegal logging, agricultural expansion, and infrastructure development. This study aims to analyze the rate of deforestation occurring in GLNP from 2008 to 2023, to examine land cover changes in the park up to 2033, and to assess community attitudes, perceptions, and participation related to deforestation in the GLNP area. The methods employed include multi-temporal satellite image analysis (Landsat 5 and Landsat 8) using supervised classification through Google Earth Engine (GEE) and Geographic Information System (GIS) tools. Data accuracy was evaluated using ground truth validation, along with an assessment of community perceptions and participation regarding land cover changes. The results indicate that during the study period, forest area decreased by approximately 18,822.71 hectares (2.38%), accompanied by an increase in shrubland and other non-forest land covers, indicating gradual land conversion. The dominant factors driving deforestation in GLNP include proximity to roads and settlements. Future deforestation rates were predicted using a Cellular Automata–based spatial modeling approach, which estimates land conversion patterns in the absence of mitigation measures. Deforestation in the GLNP area is closely linked to the role of surrounding communities; the findings reveal that local communities are generally less actively involved and less willing to contribute to conservation efforts in GLNP. This study provides important insights for conservation planning and sustainable land-use policy formulation in Gunung Leuser National Park.

Keywords: *Cellular Automata; satellite imagery; deforestation; Google Earth Engine; Gunung Leuser National Park and land cover.*

I. INTRODUCTION

Gunung Leuser National Park (GLNP) is one of the five national parks first established in Indonesia, covering a total area of 830,268.95 ha. The Leuser Ecosystem possesses exceptionally high habitat diversity, ranging from coastal zones and carbon-rich swamp forests to lowland forests, hills, lower montane and upper montane forests, extending to the summit of Mount Leuser at an elevation of nearly 3,500 m above sea level. These conditions result in extraordinarily high biodiversity, making GLNP the only conservation area in Indonesia that still supports four critically endangered large mammal species.Another important value of GLNP is its role as a major water provider for approximately four million people in the provinces of Aceh and North Sumatra. Well-managed tropical forest conservation areas are characterized by substantially higher forest cover compared to other land-cover types. Therefore, periodic measurement of forest-cover change using standardized and scientifically accountable methods is essential. This study aims to assess the deforestation rate in GLNP during the 2004–2023 period, with the resulting information serving as a baseline for evaluating management effectiveness in subsequent periods.Forests within the Leuser Ecosystem, including those in GLNP, are highly enriched with tropical hardwood species such as Dipterocarpaceae, which are commercially valuable and command high market prices. This condition exposes the area to threats from illegal logging, which is often followed by the expansion of agricultural land and plantations, including coffee, cocoa, rubber, and oil palm.

These factors significantly influence deforestation rates in GLNP and its surrounding areas. Deforestation exerts substantial negative impacts on ecological functions, increasing erosion risk, disrupting hydrological cycles, and reducing ecosystem services such as pollination and pest regulation. Consequently, these impacts also affect the economic and social systems of communities residing in five regencies in Aceh and two regencies in North Sumatra.The trend of deforestation rates has shown a continuous increase over time, indicating a steady decline in forest cover and its conversion into non-forest land, primarily driven by anthropogenic activities, particularly illegal agricultural and plantation expansion. Therefore, it is necessary to develop spatial land-cover change models to predict deforestation rates over a defined period. A ten-year projection period is considered ideal, as it produces more significant and interpretable results than a five-year timeframe. The availability of ten-year predictive outcomes enables park managers and stakeholders to implement strategic measures aimed at suppressing deforestation over larger areas.Deforestation and forest degradation are among the most critical environmental issues of global concern. Currently, environmental issues rank among the top three global challenges receiving widespread attention. Environmental degradation occurring in a particular country or region not only affects the local area but also has transboundary and global implications. Due to its urgency and broad impacts, environmental issues are no longer confined to scientific discourse but have become central topics in global political decision-making, as policy failures may have profound consequences for ecosystems and human livelihoods. Deforestation is a major driver of global warming, which refers to the increase in global temperatures resulting from ecosystem imbalance caused by rising average atmospheric temperatures.

Global warming leads to more severe consequences, ultimately manifesting as climate change, which threatens the sustainability of life on Earth.The use of remote sensing techniques to observe land-cover change and spatial variability without direct field interaction is considered highly efficient. Multi-temporal datasets facilitate the identification of major land-cover changes and their spatial patterns (Hanif et al., 2015). Advances in computer technology and the long-term operation of the Landsat satellite program have enabled the tracking of environmental changes over several decades. When integrated with Geographic Information Systems (GIS), remote sensing has proven effective in detecting environmental features such as vegetation cover, forest transitions, and specific variations in land-cover change over time (Roy & Roy, 2010).GIS and satellite-based image analysis are widely used as spatial planning instruments to visualize and interpret landscape dynamics and spatial relationships (Piekarczyk, 2014). For example, remote sensing imagery provides up-to-date land-cover information, particularly for forest areas that are difficult to access through field surveys. Moreover, remote sensing data such as Landsat imagery have been available globally since 1972, enabling continuous monitoring of land-cover change (USGS, 2013). GIS, on the other hand, is well suited for computer-based geometric analysis of land-use patterns. The integration of these two disciplines allows them to complement and enhance each other effectively (Abdel Rahman et al., 2016).The GLNP conservation area has experienced land-use changes that have converted vegetated forest cover into dryland agriculture, oil palm and rubber plantations, and settlements. Increasing land demand driven by population growth has facilitated greater access into the GLNP area.

Analysis of land cover and land use in GLNP and its buffer zones, along with their temporal changes, is essential for understanding existing land-use conditions and identifying patterns of land-cover transformation across different time periods. Knowledge of these conditions and patterns provides a scientific basis for developing management directives and policy recommendations for GLNP, informed by the results of spatial analyses. Such analyses require land-cover and land-use data derived from Landsat satellite imagery, which are interpreted into land-cover and land-use maps for GLNP and its surrounding buffer areas.The presence of infrastructure intersecting the GLNP area has increased community access, posing potential threats to the existence and function of GLNP as a World Heritage Site. In 2011, UNESCO listed the Tropical Rainforest Heritage of Sumatra (TRHS) as a World Heritage Site in Danger due to encroachment activities in its three constituent national parks, including GLNP, which have reduced the site's Outstanding Universal Value (OUV) (MoEF, 2020). Increased access and land claims within the park have escalated into tenurial conflicts, which may threaten the long-term integrity and conservation function of Gunung Leuser National Park.

II. METHODS

Research Location

The boundary of Gunung Leuser National Park (GLNP) used in this study is based on Decree No. SK.4039/Menhut-VII/KUH/2014,SK.6589/Menhut-VII/KUH/2014,and SK.859/MenLHK/Setjen/PLA.2/11/-2016, covering a total area of 830,268.95 ha, with approximately 75% of the area located in Aceh Province. Geographically, GLNP lies between 96°35′–98°30′ E longitude and 2°50′–4°10′ N latitude. Administratively, GLNP spans two provinces: Aceh Province, encompassing five regencies (Aceh Barat Daya, Aceh Selatan, Gayo Lues, Aceh Tamiang, and Aceh Tenggara), and North Sumatra Province, comprising two regencies (Langkat and Karo).GLNP is divided into three National Park Management Units (BPTN): BPTN Region I Tapaktuan, BPTN Region II Kutacane, and BPTN Region III Stabat. Each BPTN is further subdivided into smaller management units known as resorts. In total, GLNP consists of 25 resorts (Figure 1). This study was conducted in 2024 using satellite imagery acquired in 2008, 2013, 2018, and 2023. A five-year interval was selected based on the assumption that this temporal resolution is effective for land-cover monitoring and allows more accurate detection of land-cover changes.

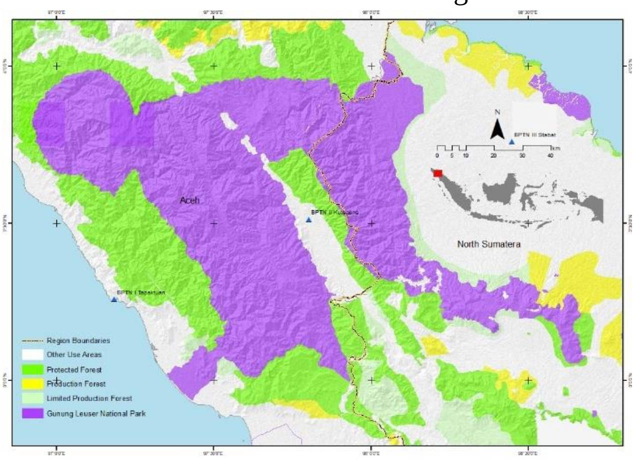

Fig 1. Map of the study area in Gunung Leuser National Park

Procedures

Information on surface conditions within the study area was obtained from remote sensing imagery, specifically Landsat 5 Thematic Mapper (TM) for the 2008 acquisition and Landsat 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) for the 2013, 2018, and 2023 acquisitions, all with a spatial resolution of 30 m. Approximately 71 satellite scenes were downloaded free of charge from the USGS website.

Image Processing and Land-Cover/Land-Use Classification

Image preprocessing began with radiometric correction using the Dark Object Subtraction (DOS1) method to convert pixel values into surface reflectance by reducing atmospheric scattering effects on dark objects. Subsequently, topographic correction was applied to minimize terrain-induced distortions.Land-cover classification was conducted using a hybrid approach, combining Maximum Likelihood Classification (MLC) with visual interpretation, supported by ground truth data and high-resolution satellite imagery such as Sentinel-2A (10 m) and SPOT-5 (5 m). The supervised classification produced spectral land-cover classes, while visual interpretation was used to convert land-cover classes into land-use categories and to refine classification outputs.The classification system followed the Indonesian National Standard (SNI 7645-1:2014), modified to emphasize land-cover classes relevant to deforestation analysis. Land-cover classes such as forest and water were derived directly from the MLC results, whereas land-use classes such as settlements and paddy fields were obtained through class derivation and visual interpretation.Postclassification processing included the application of a majority filter and class merging to reduce classification noise. Final classification accuracy was evaluated using overall accuracy and the kappa coefficient to assess classification reliability.

Ground Truth Data and Accuracy Assessment

Field data were obtained from patrol activities using the Spatial Monitoring and Reporting Tool (SMART) conducted by the Gunung Leuser National Park Authority in collaboration with partners such as WCS-IP, FKL, and OIC, and complemented by high-resolution satellite imagery. A total of 3,439 points or polygons were used as training areas to build the forest-cover classification model. Additionally, 440 independent points were used for accuracy assessment of the forest-cover model. Accuracy assessment was performed only for the 2023 satellite imagery, under the assumption that classification accuracy would be comparable for earlier years due to the use of consistent sensors and classification methods across all periods.

Land-Cover Change and Deforestation Rate Analysis

Land-cover change was analyzed by comparing classification results from 2008, 2013, 2018, and 2023, with a primary focus on changes in forest cover. Deforestation was calculated as the difference in forest area between two time periods, referring to net deforestation, which accounts for reductions in deforestation due to reforestation. Annual deforestation rates were calculated using formulas linking forest-area change to the time interval, while annual percentage deforestation rates were computed using the annual percentage change formula.

Deforestation Prediction Assessment and Analysis

Forest-to-non-forest transitions were modeled by incorporating key spatial driving factors, including distance to roads, settlements, and rivers, measured using Euclidean distance analysis. Proximity to roads and settlements increases the likelihood of forest conversion due to improved access and human activities, while proximity to rivers is associated with erosion and land-use pressure.The influence of these factors on land-cover change was statistically analyzed using Pearson correlation analysis, which measures the strength and direction of linear relationships between independent variables (distance metrics) and the probability of land-cover change. Significant correlations (p-value < 0.05) and correlation coefficients (r values approaching ± 1) were considered indicators of dominant driving factors.After identifying dominant drivers, spatial modeling was performed using the Cellular Automata (CA) algorithm implemented in the Modules for Land Use Change Simulations (MOLUSCE) plugin.

The model integrated multi-temporal land-cover data, driving factors, and historical forest-cover change patterns from 2003–2013 for calibration. Simulations were conducted to project land-cover changes for the 2023–2033 period under various scenarios of infrastructure development, population growth, and land-use policy. Model validation employed the Kappa Index and Area Under the Curve (AUC) to evaluate the agreement between simulated and observed patterns. The model was able to identify areas with a high risk of forest-to-non-forest conversion, providing a decision-support tool for sustainable land-cover management. Additionally, logistic regression analysis was used to model the probability of forest degradation and deforestation, with independent variables including distance to settlements, roads, and rivers, and regression coefficients representing the influence of each variable on land-cover change. Annual deforestation rate formulas were also applied to quantify the speed of forest-cover change over time.

Data Analysis

Land-cover and land-use change analyses were conducted using multi-temporal Landsat imagery from 2008, 2013, 2018, and 2023, supported by visual interpretation and field verification to produce land-cover and land-use maps. Spatial–temporal dynamics of land cover were analyzed to generate land-use maps for the study period.Deforestation rate analysis and ten-year prediction were conducted using 2023 land-use data, supported by GIS overlay data (roads, rivers, and settlements) and spatial modeling using the MOLUSCE plugin in QGIS. This process resulted in predictive maps of land-cover change and deforestation rates for the ten-year projection period. These analytical steps support a comprehensive understanding of land-cover dynamics and anthropogenic pressures, providing a scientific basis for sustainable management recommendations for Gunung Leuser National Park.

III. RESULT AND DISCUSSION

Geographical Conditions of the Study Area

Gunung Leuser National Park (GLNP) is one of the five earliest national parks established in Indonesia, officially designated on 7 March 1980 through the Decree of the Minister of Agriculture No. 811/Kpts/Um/II/1980. The area of GLNP has undergone several revisions, with the most recent designation issued by the Ministry of Forestry defining a total area of 830,268.95 hectares, extending across the provinces of Aceh and North Sumatra.GLNP constitutes a critical component of the Leuser Ecosystem, which covers approximately 2.5 million hectares and is ecologically connected to the forested landscapes of the Ulu Masen area (Figure 2). This ecosystem is characterized by exceptionally high biodiversity, encompassing a wide range of habitats from coastal zones to montane environments, reaching elevations of nearly 3,500 meters above sea level.

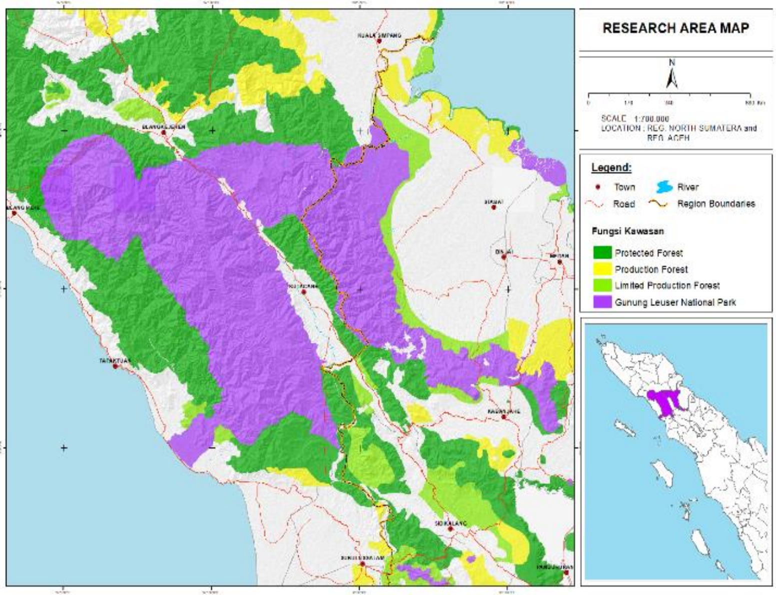

Fig 2. Map of the deforestation rate study area in Gunung Leuser National Park

Dynamics of Land-Cover Change in Gunung Leuser National Park (2008, 2013, 2018, and 2023)

Land-cover change analysis was conducted across the entire area of Gunung Leuser National Park (GLNP), covering a total area of 830,268.95 ha, with approximately 75% of the area located in Aceh Province and the remaining 25% in North Sumatra Province. The study was carried out in 2024 using satellite imagery acquired in 2008, 2013, 2018, and 2023. A five-year temporal interval was selected based on the assumption that this time span is effective for monitoring land-cover dynamics. Data from the years 2008, 2013, 2018, and 2023 were included to assess the most recent land-cover conditions in GLNP and its surrounding areas.The interpretation of remote sensing imagery using Google Earth Engine (GEE), employing ten land-cover classification classes as described above, produced estimates of area extent and percentage coverage for each land-cover class within Gunung Leuser National Park (GLNP) for the study years 2008, 2013, 2018, and 2023, as presented in Table 1.

Forest Area Decline

Forest cover remained the dominant land-cover class (>90%) throughout the study period; however, a consistent decline was observed. Forest area decreased from 791,522 ha (95.31%) in 2008 to 772,700 ha (93.05%) in 2023. This reduction reflects ongoing land conversion driven by forest encroachment, plantation expansion, road accessibility, weak law enforcement, socio-economic pressures, and limited availability of alternative livelihoods for local communities.

Shrubland Reduction

Shrubland area exhibited notable fluctuations, reaching a peak in 2013 before declining sharply to 22,308 ha in 2023. This trend indicates substantial conversion of shrubland into more productive land uses, particularly agriculture and plantations.

Increase in Grassland

Grassland area increased markedly from 1,683 ha in 2008 to 8,820 ha in 2023, suggesting progressive forest degradation and failed restoration processes. In these areas, forest cover has been transformed into grass-dominated landscapes that provide limited ecological support compared to natural forest ecosystems.

Fluctuation in Bare Land

The extent of bare land showed temporal variability, increasing slightly from 101 ha in 2008 to 553 ha in 2023. This change is associated with infrastructure development activities and selective logging operations within and around the park.

Rapid Expansion of Gardens and Plantations

Areas classified as gardens and plantations remained relatively low and stable until 2018, after which a sharp increase was recorded, reaching 6,621 ha (0.80%) in 2023. This expansion is primarily attributed to smallholder plantation development constrained by limited access to legally available land, which in turn has driven encroachment into the GLNP area.

Changes in Dryland Agriculture

Dryland agriculture experienced a substantial increase in 2018, followed by a decline in 2023 to approximately 1,205 ha. This reduction reflects land-use conversion into gardens, settlements, or grasslands, as well as the influence of enforcement actions and ecosystem restoration efforts implemented in recent years.

Increase in Mixed Dryland Agriculture with Shrub

Mixed dryland agriculture with shrub cover increased significantly from 2,898 ha in 2008 to 17,121 ha in 2023, indicating extensive conversion of forest and shrubland into mixed agricultural systems. This trend has been driven by the expansion of commercial agriculture and limited awareness of conservation principles among land users.

Expansion of Rice Fields

New rice-field development increased markedly from 6.48 ha during 2008–2013 to 78 ha in 2023, reflecting a response to rising food demand associated with population growth in areas surrounding Gunung Leuser National Park (GLNP).

Settlement Growth

Although still occupying a very small proportion of the total area (<0.01%), settlement land increased from 12 ha in 2008 to 77 ha in 2023, indicating growing pressure from residential development within buffer zones and, to a limited extent, inside conservation areas.

Relatively Stable Water Bodies

The extent of water bodies showed a slight increase from 712 ha in 2008 to 967 ha in 2023. This change is influenced by hydrological dynamics, climate variability, and land degradation processes that have expanded inundated areas and altered river flow patterns.

Table 1. Land-Cover Changes in Gunung Leuser National Park (2008, 2013, 2018, and 2023)

Land Use	Land-Cover Area (ha)							
	2008	%	2013	%	2018	%	2023	%
Forest	791.522,47	95,31	784.178,22	94,43	775.369,11	93,37	772.699,76	93,05
Shrubland	32.795,75	3,95	34.641,82	4,17	32.453,24	3,91	22.308,49	2,69
Grassland	1.683,15	0,2	2.760,98	0,33	5.320,08	0,64	8.820,10	1,06
Bare Land	100,94	0,01	689,97	0,08	182,68	0,02	553,46	0,07
Plantations	629,36	0,08	632,14	0,08	669,79	0,08	6.621,20	0,8
Dryland Agriculture	90,55	0,01	91,32	0,01	1.857,89	0,22	1.205,71	0,15
Mixed Dryland Agriculture with Shrub	2.898,46	0,35	6.712,50	0,81	13.825,39	1,66	17.121,21	2,06
Rice Fields	6,48	0	6,48	0	7,54	0	78,03	0,01
Settlements	12,37	0	15,73	0	55,62	0,01	77,23	0,01
Water Bodies	712,73	0,09	723,1	0,09	711,37	0,09	967,51	0,12
Total	**830.452,26**	**100**	**830.452,26**	**100**	**830.452,71**	**100**	**830.452,70**	**100**

Note: (–) indicates a decrease in area

Forest area declined consistently over the study period, although it remained the dominant land-cover type. Human activities such as plantation development, agriculture, and settlement expansion increased significantly. Mixed agriculture and grassland emerged as the fastest-growing land-cover classes, with the potential to replace forest and shrubland areas. These indications of substantial land-use conversion warrant serious attention in the context of conservation and long-term sustainability of Gunung Leuser National Park. Consistent with these findings, Rahmawaty et al. (2021) detected significant land-cover changes from forest to plantations, rice fields, and settlements using GIS-based analysis complemented by ground-truth verification. Similarly, Ginting et al. (2023) reported a continuous decline in forest cover and identified a trend indicating that pressure on tree cover began to level off after 2020–2022, reflecting a pattern of decelerating forest loss.Table 2 shows how each land-cover class changed from one period to the next, in terms of both area (ha) and percentage relative to the previous land-cover extent. Positive values indicate an increase in land-cover area, whereas negative values indicate a decrease or conversion to other land-use types.Forest cover declined consistently from 2008 to 2023, with the rate of decline slowing during the most recent period (2018–2023), indicating that land-conversion pressures may be becoming more controlled. Shrubland initially increased and then declined sharply, particularly in the final period, due to conversion into grassland, mixed dryland agriculture, or plantations. Grassland area increased significantly across all periods, indicating ongoing forest degradation and/or new land clearing.

Table 2. Area and Percentage of Land-Cover Changes in GLNP

Land-Cover Class	**Land-Cover Area Changes (ha)**					
	2008-2013	**%**	**2013-2018**	**%**	**2018-2023**	**%**
Forest	-7.344,25	-0,93	-8.809,11	-1,12	-2.669,35	-0,34
Shrubland	1.846,07	5,63	-2.188,58	-6,32	-10.144,75	-31,26
Grassland	1.077,83	64,04	2.559,10	92,69	3.500,02	65,79
Bare Land	589,03	583,54	-507,29	-73,52	370,78	202,97
Plantations	2,78	0,44	37,65	5,96	5.951,41	888,55
Dryland Agriculture	0,77	0,85	1.766,57	1.934,48	-652,18	-35,10
Mixed Dryland Agriculture with Shrub	3.814,04	131,59	7.112,89	105,96	3.295,82	23,84
Rice Fields	-	-	1,06	16,36	70,49	934,88
Settlements	3,36	27,16	39,89	253,59	21,61	38,85
Water Bodies	10,37	1,45	-11,73	-1,62	256,14	36,01
Total	**- 0,0**		**0,45**		**-0,01**	

Note: (–) indicates a decrease in area

Bare land exhibited fluctuating patterns, with alternating increases and decreases, indicating small-to medium-scale land-clearing activities. Gardens and plantations increased sharply during the most recent period, reflecting large-scale expansion into areas previously classified as forest or shrubland. Dryland agriculture expanded rapidly during the middle period but declined toward the end, likely due to relocation to other land-use types or partial reversion to forest or shrubland.Mixed dryland agriculture with shrub cover continued to grow substantially, although the growth rate slowed slightly during the final period, indicating extensive conversion from forest and shrubland. Rice fields began to expand significantly in the most recent period, likely in response to increasing local food demand. Settlement areas also increased, particularly during **2013–2018**, indicating population pressure and development around GLNP. The extent of water bodies remained relatively stable overall, with an increase observed in the final period, influenced by climatic factors, dam construction, and wetland restoration efforts.

Description of Land-Cover Changes in Gunung Leuser National Park During the 2008–2013 Period

Based on the classification results, land-cover changes during the 2008–2013 period are presented in Table 3, which illustrates changes in each land-cover class between 2008 and 2013. The results can be described as follows.Forest area decreased by 7,344.25 ha (–0.93%), declining from 791,522.47 ha in 2008 to 784,178.23 ha in 2013. In contrast, water bodies increased by 10.37 ha (1.45%), expanding from 712.73 ha in 2008 to 723.10 ha in 2013. Garden and plantation areas increased slightly by 2.78 ha (0.44%), from 629.22 ha to 632.14 ha over the same period.Bare land experienced a substantial increase of 589.03 ha

(583.54%), rising sharply from 89.19 ha in 2008 to 689.97 ha in 2013, indicating intensified land-clearing activities. Grassland area also increased significantly by 1,077.83 ha (64.04%), from 1,647.24 ha to 2,760.98 ha, suggesting forest degradation and land conversion processes.Dryland agriculture expanded marginally by 0.77 ha (0.85%), increasing from 90.55 ha in 2008 to 91.32 ha in 2013. Mixed dryland agriculture with shrub cover showed a pronounced increase of 3,814.04 ha (131.59%), expanding from 2,898.46 ha to 6,712.50 ha, indicating substantial conversion from forest and shrubland areas.

Settlement area also increased by 3.36 ha (27.16%), from 12.37 ha in 2008 to 15.73 ha in 2013, reflecting increasing residential pressure within and around Gunung Leuser National Park. During this period, the most significant land-cover change occurred in the forest class, which declined by 7,344.25 ha. Although this reduction represents only 0.93% in relative terms, it is substantial given that forest cover dominates the overall land-cover composition of Gunung Leuser National Park. The reduction in forest area was redistributed into several other land-cover classes, with the most notable increase observed in bare land, which expanded by 589.03 ha (583.54%).During this period, forest-to-non-forest conversion was predominantly driven by illegal activities, including illegal logging and the clearing of forest areas for plantations, agriculture, and settlements. One notable example occurred in PIR ADB Besitang Village, which accommodated former Aceh refugees displaced by the security conflict in Aceh Province prior to the Helsinki Peace Agreement. These displaced communities were settled in an area known as *Barak Induk*, where public and social infrastructure were subsequently developed.

Table 3. Land-Cover Transition Matrix between 2008 and 2013

	Land Cover in 2013										
	Land-Cover Class	Water	Forest	Plantations	Bare Land	Grassland	Dryland Agriculture	Mixed Dryland Agriculture with Shrub	Settlements	Shrubland	Rice Fields	Grand Total
Land Cover in 2008	Water	696,03	0,10	-	0,27	-	-	-	1,66	14,67	-	712,73
	Forest	0,58	781.649,22	-	79,41	1,98	-	193,16	-	9.598,13	-	791.522,47
	Plantations	-	-	629,22	-	-	-	-	-	0,15	-	629,37
	Bare Land	-	-	-	89,19	-	-	4,01	-	7,74	-	100,94
	Grassland	-	-	-	7,92	1.647,24	-	-	-	27,99	-	1.683,15
	Dryland Agriculture	-	-	-	-	-	90,55	-	-	-	-	90,55
	Mixed Dryland Agriculture with Shrub	-	-	1,89	-	-	0,26	2.895,21	1,10	-	-	2.898,46
	Settlements	-	-	-	-	-	-	-	12,37	-	-	12,37
	Shrubland	26,50	2.528,91	1,04	513,18	1.111,76	0,50	3.620,12	0,60	24.993,14	-	32.795,75
	Rice Fields	-	-	-	-	-	-	-	-	-	6,48	6,48
	Grand Total	723,10	784.178,23	632,14	689,97	2.760,98	91,32	6.712,50	15,73	34.641,82	6,48	830.452,28

Similar patterns have also been observed in other conservation areas, such as Bukit Barisan Selatan National Park (TNBBS), where smallholder shifting cultivation has had substantial implications as a major driver of deforestation (Dove, 1993). In addition, logging activities conducted by Forest Concession Holders (HPH) as well as illegal loggers have been identified as key causes of deforestation. Local communities and shifting cultivators often merely occupy the "vacuum" created by these concessionaires and illegal logging activities (Kummer & Turner, 1994).These findings are consistent with the study by Rahmawaty et al. (2020), which reported that pressures from illegal activities—such as logging and land-use conversion—are reflected in declining forest conditions, while mitigation responses indicate the potential for a slowdown in forest-cover loss. Furthermore, Rahmawaty et al. (2022), employing an integrated approach combining satellite imagery, GIS, and the Driving–Pressure–State–Impact–Response (DPSIR) framework to assess land-cover change and forest degradation at the watershed scale, found that pressures from illegal logging and land-use conversion were clearly manifested in changes to the *state* component, resulting in a significant decline in forest cover condition.

Description of Land-Cover Changes in the Gunung Leuser National Park Area during the 2013–2018 Period

Based on satellite image acquisition processed using Google Earth Engine (GEE), the surface conditions of the study area were analyzed for the 2013 and 2018 observation years. The resulting imagery was subsequently classified into land-cover classes using a combined approach of Maximum Likelihood Classification (MLC) and visual interpretation.Based on the land-cover classification results, changes in land cover during the 2013–2018 period were identified, as presented in Table 4, which summarizes the changes in each land-cover class between 2013 and 2018. The results indicate that forest area decreased by 8,809.22 ha (−1.12%), declining from 784,178.23 ha in 2013 to 775,369.01 ha in 2018. The water bodies class decreased by 12.00 ha (−1.66%), from 723.10 ha in 2013 to 711.10 ha in 2018.The plantation area increased by 37.59 ha (5.95%), expanding from 632.14 ha in 2013 to 669.73 ha in 2018. In contrast, bare land declined substantially by 507.28 ha (−73.52%), decreasing from 689.97 ha in 2013 to 182.68 ha in 2018. Grassland experienced a marked increase of 2,559.10 ha (92.69%), growing from 2,760.98 ha in 2013 to 5,320.08 ha in 2018.Dryland agriculture expanded significantly by 1,766.57 ha (1,934.51%), increasing from 91.32 ha in 2013 to 1,857.89 ha in 2018. Similarly, mixed dryland agriculture with shrub increased by 7,112.89 ha (105.96%), from 6,172.50 ha in 2013 to 13,825.39 ha in 2018. Settlement areas also expanded by 39.88 ha (253.48%), from 15.73 ha in 2013 to 55.62 ha in 2018.Meanwhile, shrubland decreased by 2,188.60 ha (−6.32%), from 34,641.82 ha in 2013 to 32,453.23 ha in 2018, while rice fields increased slightly by 1.06 ha (16.28%), from 6.48 ha in 2013 to 7.54 ha in 2018.Similar to the previous period, significant changes during this period were also observed in the forest land-cover class, which declined by 8,809.22 ha (1.12%). The reduction in forest area was redistributed into several other land-cover classes, with the most substantial increase occurring in dryland agriculture, which expanded by 1,766.57 ha, representing an increase of 1,934.51%.

Table 4. Land-Cover Transition Matrix between 2013 and 2018

		Land Cover in 2018										
	Land-Cover Class	Water	Forest	Plantations	Bare Land	Grassland	Dryland Agriculture	Mixed Dryland Agriculture with Shrub	Settlements	Shrubland	Rice Fields	Grand Total
Land Cover in 2013	Water	703,45	7,48	-	-	0,09	0,10	1,04	-	10,80	0,16	723,10
	Forest	1,08	774.896,55	26,30	151,03	151,62	30,66	906,66	-	8.014,33	-	784.178,23
	Plantations	-	-	614,32	-	-	-	-	17,64	0,18	-	632,14
	Bare Land	-	0,09	0,68	0,27	370,98	-	-	-	317,95	-	689,97
	Grassland	-	0,63	-	-	2.184,26	-	-	-	576,09	-	2.760,98
	Dryland Agriculture	0,18	-	-	-	-	90,57	-	0,57		-	91,32
	Mixed Dryland Agriculture with Shrub	1,11	-	6,28	-	-	1.125,89	5.563,22	13,49	2,24	0,27	6.712,50
	Settlements	-	-	-	-	-	-	-	15,73	-	-	15,73
	Shrubland	5,29	464,25	22,16	31,38	2.613,13	610,68	7.354,46	8,19	23.531,65	0,63	34.641,82
	Rice Fields	-	-	-	-	-	-	-	-	-	6,48	6,48
	Grand Total	711,10	775.369,01	669,73	182,68	5.320,08	1.857,89	13.825,39	55,62	32.453,23	7,54	830.452,28

A comparable pattern has been documented in Bantimurung Bulusaraung National Park (TN Babul), Maros Regency, South Sulawesi, Indonesia. The designation of previously managed forest lands as a national park in 2004 fundamentally altered long-standing land-use practices and livelihood activities of local communities within the park boundaries. These communities have historically relied on forest resources to sustain their livelihoods, resulting in persistent human–forest interactions. Consequently, conservation management in TN Babul faces the challenge of balancing ecological protection with socio-economic realities. Effective management strategies must therefore incorporate community engagement and livelihood considerations while safeguarding ecosystem integrity (Awang, 2006).

Land-Cover Change Dynamics in Gunung Leuser National Park during the 2018–2023 Period

Based on the land-cover classification results, land-cover changes during the 2018–2023 period are summarized in Table 4.6, which presents transitions for each land-cover class between 2018 and 2023. During this period, forest cover declined by 2,669.34 ha (0.34%), decreasing from 775,369.01 ha in 2018 to 772,699.66 ha in 2023. In contrast, water bodies increased by 256.06 ha (36.01%), expanding from 711.10 ha to 967.16 ha, likely reflecting hydrological dynamics and land degradation processes.Substantial expansion was observed in plantations, which increased by 5,951.47 ha (888.63%), from 669.73 ha in 2018 to 6,621.20 ha in 2023, indicating accelerated land conversion. Open land also increased by 370.78 ha (202.96%), while grassland expanded by 3,500.02 ha (65.79%), suggesting ongoing forest degradation and incomplete restoration processes. Conversely, dryland agriculture declined by 652.19 ha (35.10%), potentially due to conversion into plantations, mixed agricultural systems, or grassland.The mixed dryland agriculture–shrub class continued to expand, increasing by 3,295.82 ha (23.84%), while settlement areas grew by 21.62 ha (38.86%), reflecting persistent anthropogenic pressure. A pronounced reduction occurred in shrubland, which declined by 10,144.73 ha (31.26%), largely transitioning into plantations, grassland, and mixed agricultural uses. Although still limited in absolute extent, paddy fields increased sharply by 70.50 ha (935.41%), indicating a growing response to local food demand.

Compared with the previous period (2013–2018), forest loss during 2018–2023 was markedly lower (2,669.34 ha vs. 8,809.22 ha), suggesting a relative slowdown in deforestation rates. However, forest conversion continued, predominantly into plantations and paddy fields, which represent the most rapidly expanding land-use classes during this period.This period represents the lowest level of forest-cover loss compared to previous intervals, with forest-to-non-forest conversion totaling 2,669.35 ha (0.34%) over five years. The observed slowdown in deforestation coincides with a policy shift introduced in 2018, when the Government of Indonesia, through the Directorate General of Natural Resources and Ecosystem Conservation (KSDAE), Ministry of Environment and Forestry, promoted collaborative forest management with local communities.This policy framework emphasizes mutual trust, shared benefits, and collective responsibility, aiming not only to conserve ecosystems but also to enhance community participation and livelihood development in areas surrounding conservation forests. Within this framework, conservation partnerships are formally defined under Regulation of the Director General of KSDAE No. P.6/KSDAE/SET/Kum.1/6/2018, which characterizes such partnerships as cooperative arrangements between protected-area management authorities or permit holders and local communities, grounded in principles of mutual respect, trust, and benefit-sharing (Prayitno, 2020).

Table 5. Land-Cover Transition Matrix between 2018 and 2023

		Land Cover in 2023										
Land Cover in 2018	Land-Cover Class	Water	Forest	Plantations	Bare Land	Grassland	Dryland Agriculture	Mixed Dryland Agriculture with Shrub	Settlements	Shrub land	Rice Fields	Grand Total
	Water	706,52	-	-	-	-	-	0,32	-	4,26	-	711,10
	Forest	161,21	770.117,93	424,52	305,45	927,91	56,09	1.109,92	1,72	2.262,11	2,15	775.369,01
	Plantations	0,00	2,89	427,46	0,37	-	21,46	161,32	8,15	47,52	0,56	669,73
	Bare Land	-	2,00	8,00	19,47	9,79	-	38,36	-	104,38	0,69	182,68

	Grassland	-	20,85	-	32,63	3.746,84	-	119,68	-	1.399,22	0,87	5.320,08
	Dryland Agriculture	0,52	0,24	303,10	4,33	-	237,73	1.269,51	1,99	38,75	1,73	1.857,89
	Mixed Dryland Agriculture with Shrub	29,75	51,01	2.586,79	20,57	5,94	672,56	8.707,78	11,59	1.710,29	29,12	13.825,39
	Settlements	0,05	-	2,18	-	-	3,85	3,44	44,17	1,38	0,54	55,62
	Shrubland	68,73	2.504,74	2.867,78	170,65	4.129,62	213,92	5.710,88	8,71	16.739,96	38,23	32.453,23
	Rice Fields	0,40	0,00	1,36	-	-	0,10	-	0,90	0,63	4,15	7,54
	Grand Total	967,16	772.699,66	6.621,20	553,47	8.820,10	1.205,71	17.121,21	77,23	22.308,49	78,04	830.452,28

Conservation partnerships are implemented through two main modalities: community-empowerment–oriented conservation partnerships and ecosystem-restoration–oriented conservation partnerships. In the community empowerment scheme, local communities are directed to designated utilization zones, with due consideration given to accessibility, local socio-economic conditions, and the potential of non-timber forest products or aquatic resources that are not subject to strict protection. In contrast, ecosystem restoration partnerships focus on collaborative efforts to restore degraded forest ecosystems (Mutiono, 2020).The ecosystem restoration–oriented conservation partnership plays a critical role in reducing deforestation rates in Gunung Leuser National Park (GLNP). Through this partnership model, local communities are formally engaged as collaborative managers, allowing them to participate in forest management and utilize resources in a regulated manner while prioritizing ecological sustainability principles. This approach not only mitigates illegal land conversion but also strengthens local stewardship and compliance with conservation objectives.

Similar partnership-based innovations have been implemented in other conservation areas in Indonesia, including Rawa Aopa National Park, Paliyan Wildlife Reserve, and Teluk Cenderawasih National Park (MoEF, 2015). Teluk Cenderawasih National Park (TCNP), which represents coral reef, coastal, mangrove, and tropical lowland island forest ecosystems in Papua, has experienced substantial ecological and physical degradation in recent years. This decline has been primarily driven by destructive human activities, such as unsustainable fishing practices involving explosives and poisons, as well as excessive extraction of marine biota.Addressing such complex conservation challenges requires collaborative partnerships among multiple stakeholders. Conservation partnerships in TCNP have demonstrated potential not only to mitigate and reverse environmental degradation but also to enhance community empowerment and socio-economic development in areas surrounding conservation zones. These experiences underscore the broader applicability of collaborative conservation partnerships as an effective governance mechanism for balancing ecosystem protection with local livelihood needs.

Deforestation Rates Based on Land-Cover Dynamics and Ten-Year Deforestation Projections in Gunung Leuser National Park

Deforestation rate is a metric that quantifies the speed at which forest cover is lost within a defined time period. In this study, deforestation rates in Gunung Leuser National Park (GLNP) were calculated using a formula adapted from Dariono (2018). Two primary indicators were derived from the analysis:

1. an absolute annual deforestation rate of 1,245.84 ha year^{-1}, and
2. an annual percentage deforestation rate of 0.1585% year^{-1}.

Forest cover in GLNP declined from 791,522.47 ha in 2008 to 772,699.76 ha in 2023, resulting in a total forest loss of 18,822.71 ha over a 15-year period. This corresponds to an average forest-cover reduction of approximately 1,254.84 ha per year, indicating a relatively persistent pressure on forest resources within this protected area.An annual loss of approximately 1,246 ha of forest cover represents a substantial impact, particularly given GLNP’s status as a nationally and globally significant conservation area. The park plays a critical role in maintaining biodiversity and ecosystem stability, including serving as a key habitat for Sumatran orangutans (*Pongo abelii*), Sumatran tigers (*Panthera tigris sumatrae*), and Sumatran elephants

(*Elephas maximus sumatranus*).Although the annual percentage deforestation rate (0.1585%) may appear relatively small, even marginal annual losses can accumulate into significant ecological degradation over time in large protected landscapes such as GLNP. Cumulatively, these losses can undermine habitat integrity, ecological connectivity, and ecosystem services if not effectively mitigated.As illustrated in Figure 3, land-cover dynamics during the 2003–2023 period indicate a total deforestation area of 22,656.29 ha, alongside 3,833.48 ha of reforested land, 768,866.18 ha of persistent forest, and 35,096.33 ha of stable non-forest areas. These figures highlight the complex balance between forest loss and recovery processes, emphasizing the importance of sustained conservation interventions and adaptive management strategies to curb long-term deforestation trends in GLNP.

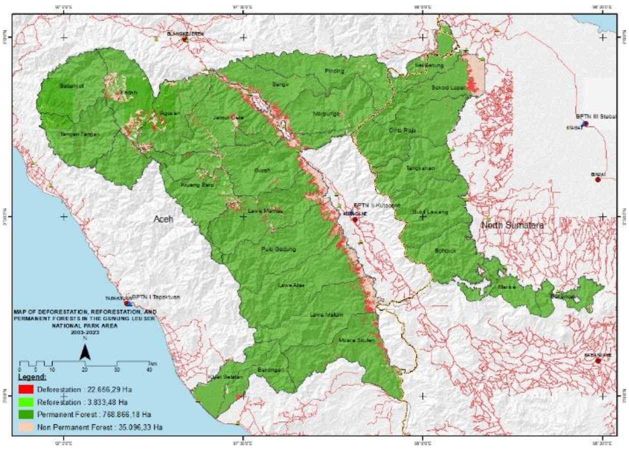

Fig 3. Distribution Map of Deforestation in the TNGL Area (2003–2023)

The factors driving deforestation in the TNGL area are diverse, ranging from illegal activities such as forest encroachment and illegal logging to land conversion for agriculture, plantations, and infrastructure development. According to Rahmawati (2020), deforestation is primarily driven by economic pressures, where land is converted from dryland farming and shrubs to non-agricultural uses (e.g., settlements and infrastructure). Social and ecological pressures also contribute to forest loss, but economic factors remain the principal driver.Deforestation not only results in the loss of wildlife habitats for species such as orangutans, Sumatran tigers, and elephants, but also contributes to global climate change through the release of carbon emissions. Therefore, even if the percentage appears relatively small, this rate of deforestation warrants serious attention. Effective management measures, enhanced forest patrols, and collaboration among the government, local communities, and conservation organizations are essential to reduce forest loss and ensure the long-term preservation of GLNP.

Predicted Deforestation Rates Over the Next Decade

Spatial modeling of land-use changes in the TNGL area using the Cellular Automata (CA) method combined with an Artificial Neural Network (ANN) approach within MOLUSCE provides comprehensive insights into the dynamics of land use and deforestation.

a. Analysis of Dominant Factors in Land Cover Change

The three maps in Figure 4 represent the distribution of the nearest distance values (Euclidean distance) from each pixel in the study area to four different features or "sources": roads, settlements, and rivers. Lighter colors (white) typically indicate closer proximity, whereas darker colors (black) represent areas that are increasingly distant from the sources.Based on the conducted analysis, the resulting Pearson correlation table shows varying degrees of association. In general, these can be classified as follows (rough reference: 0.00–0.20 = very weak; 0.21–0.40 = weak; 0.41–0.70 = moderate; 0.71–1.00 = strong):

Table 6. Pearson Correlation Values of Dominant Factors in Land-Use Change

Correlation	**Proximity to "Roads"**	**Proximity to "Settlements"**	**Proximity to "Rivers"**
Proximity to "Roads"	--	0,7516	-0,0940
Proximity to "Settlements"		--	-0,0083
Proximity to "Rivers"			--

These correlations indicate that land-use change patterns are often driven by proximity to settlements, in addition to road accessibility and the presence of rivers. The combination of infrastructure factors (public facilities, social amenities, and roads) and social aspects (settlements) creates a certain “attractiveness” for land expansion, including the conversion of forest to non-forest areas. The highest correlation value (0.7516) between roads and settlements highlights that the development of land clearing from forest to non-forest frequently occurs in parallel with the expansion of nearby settlements, driven both by the demand for land and the need for supporting social infrastructure.

b. Results of Land-Cover Change Modeling Using the Artificial Neural Network Method

The results of the Transition Potential modeling conducted using the Artificial Neural Network (Multi-layer Perceptron, MLP) method within the MOLUSCE software (Modules for Land Use Change Simulation) are presented in Figure 4.12.

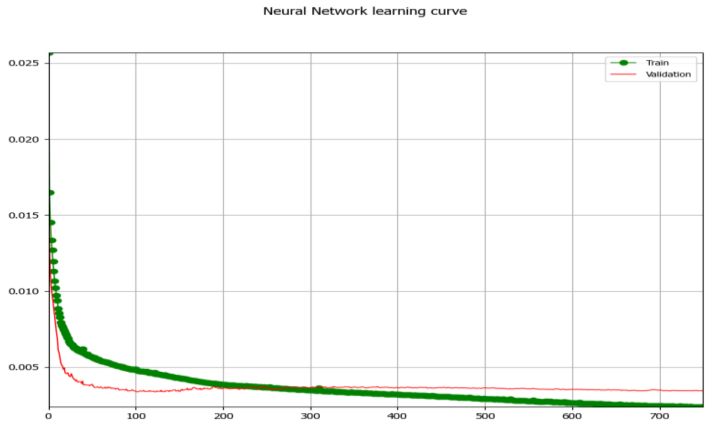

Fig 4. Learning Curve of the Artificial Neural Network

The learning curve indicates that the green line (*Train Error*) gradually decreases throughout the iteration process, reflecting the model’s ability to effectively learn land-use change patterns. In parallel, the red line (*Validation Error*), which remains relatively flat, indicates improved model performance in predicting validation data. At a certain point, the model achieved a Minimum Validation Overall Error of 0.00337, revealing the minimum error rate when tested using data outside the training set.This low error value reflects the model’s capacity to map land-use changes with a relatively high degree of accuracy. Furthermore, the Current Validation Kappa stands at 0.77957; according to Foody (2002), a Kappa value above 0.6 indicates good agreement between model predictions and reference data. Thus, the model can be considered reliable for detecting land-use changes.Nevertheless, the Δ Overall Accuracy of -0.00008 indicates a slight decrease in overall accuracy that warrants attention. Further evaluation and parameter adjustment are recommended to maximize the stability and consistency of prediction results. Although negative, this accuracy difference is minimal and still within acceptable limits.

Minor fluctuations between training and validation data suggest the need for additional attention, such as reviewing input data or extending the training period. According to Amgoth et al. (2023), such negative outcomes may indicate inconsistencies in input data during validation. They recommend parameter adjustments or increased iterations to improve model stability, as also suggested in this study.The model validation results demonstrate a relatively high accuracy level, with 95.26% of classified data matching the reference. The overall Kappa value of 0.60 indicates agreement between classification results and reference data, while the histogram Kappa of 0.76 reflects a proper class distribution. In addition, the location Kappa of 0.80 demonstrates good spatial accuracy. Overall, the model exhibits reliable performance for land-cover projection analysis. Iskandar et al. (2024) support the use of MOLUSCE with ANN for modeling land-cover change in Central Kalimantan, noting that this method effectively captures complex forest-to-oil-palm plantation conversion patterns, similar to findings in the TNGL area.By combining remote sensing techniques and spatial modeling as described above, this study highlights the degree of land-use change, particularly the conversion of forest areas to non-forest areas between 2023 and 2033. The analysis results are presented in Table 7.

Table 7. Land-Cover Area Changes by Class in 2023 and Projected for 2033

Land-Cover Class	Area (ha)			%
	Land Cover in 2023	Land Cover in 2033	Δ (Change)	
Water	967,16	754,62	- 212,54	-0,03
Forest	772.699,66	766.572,09	- 6.127,58	- 0,74
Plantations	6.621,20	6.407,94	- 213,25	- 0,03
Bare Land	553,47	388,33	- 165,13	- 0,02
Grassland	8.820,10	7.921,14	- 898,96	- 0,11
Dryland Agriculture	1.205,71	669,06	- 536,65	- 0,06
Mixed Dryland Agriculture with Shrub	17.121,21	19.917,10	2.795,88	0,34
Settlements	77,23	53,13	- 24,10	- 0,00
Shrubland	22.308,49	27.706,63	5.398,13	0,65
Rice Fields	78,04	62,23	- 15,80	- 0,00
Grand Total	830.452,28	830.452,28		

Note: (-) indicates a decrease in area

Based on Table 7, the modeled land-cover changes in Gunung Leuser National Park between 2023 and the projected year 2033 are as follows:

The area covered by water decreases from 967.16 ha to 754.62 ha, indicating a reduction of 212.54 ha, or approximately 0.03% of the total area. This decline may result from shrinkage of water bodies such as lakes or rivers due to sedimentation, climate change, or conversion to other land uses. Forests experience the most significant reduction in area, decreasing from 772,699.66 ha to 766,572.09 ha, a loss of 6,127.58 ha or roughly 0.74%. This indicates ongoing deforestation, most likely driven by the expansion of agriculture, plantations, and other human activities.Plantation areas decrease from 6,621.20 ha to 6,407.94 ha, a reduction of 213.25 ha or 0.03%. This may indicate conversion of plantations to other land uses or degradation due to climate change or unsustainable agricultural practices. Open land also declines from 553.47 ha to 388.33 ha, a reduction of 165.13 ha or approximately 0.02%, suggesting that these areas may have transitioned into shrubland, agricultural land, or even settlements. Grasslands shrink by 898.96 ha, from 8,820.10 ha to 7,921.14 ha (0.11%), likely due to conversion into agricultural land or shrubland as a result of natural succession and human intervention.Dryland agriculture decreases sharply from 1,205.71 ha to 669.06 ha, a loss of 536.65 ha or 0.06%. This decline may be caused by reduced interest in traditional farming or climate-related decreases in soil fertility. Conversely, mixed land-use areas show the largest increase, rising from 17,121.21 ha to 19,917.10 ha, an increase of 2,795.88 ha or 0.34%.

This suggests that some areas previously classified as forest, grassland, or pure agricultural land have transformed into a mixture of shrubland and subsistence farming.Settlements decrease from 77.23 ha to 53.13 ha, a reduction of 24.10 ha. Although the absolute value is small, this is somewhat unusual, as settlements typically expand. This may result from relocation or disasters leading to a reduction in permanent settlement areas. Shrubland increases from 22,308.49 ha to 27,706.63 ha, an increase of 5,398.13 ha or 0.65%, which may reflect ecological succession, whereby areas previously classified as grassland, open land, or secondary forest become increasingly covered by shrub vegetation. Paddy fields slightly decline from 78.04 ha to 62.23 ha, a reduction of 15.80 ha, possibly reflecting conversion to non-productive land or reversion to shrubland or dryland due to reduced water availability or changes in land use.Overall, the data reveal a general trend of decreasing forest and grassland cover, indicating pressures on natural ecosystems. At the same time, there is an increase in shrubland and mixed agriculture, reflecting a transformation of land into semi-natural or mixed-use forms, alongside reductions in certain classes such as paddy fields and settlements, which may require further investigation due to their atypical patterns.a. Results of Land-Cover Change Modeling Using a Predictive Model Based on Spatial and Temporal Transitions This analysis was conducted to compare land-cover change modeling using a predictive model based on spatial and temporal transitions, without incorporating variable information such as proximity to roads, settlements, and rivers.

Table 8. Land-Cover Change Model for the 2023–2033 Period Using a Transition Matrix

Land-Cover Class	Area (ha)			%
	Land Cover in 2023	Land Cover in 2033	Δ (Change)	
Water	967,16	653,36	-313,80	- 0,32
Forest	772.699,66	785.216,33	12.516,67	0,02
Plantations	6.621,20	599,30	- 6.021,90	-0,91
Bare Land	553,47	530,21	- 23,25	- 0,04
Grassland	8.820,10	2.670,68	- 6.149,42	- 0,70
Dryland Agriculture	1.205,71	82,29	- 1.123,41	- 0,93
Mixed Dryland Agriculture with Shrub	17.121,21	6.606,65	- 10.514,56	- 0,61
Settlements	77,23	10,80	- 66,43	- 0,86
Shrubland	22.308,49	33.988,62	11.680,13	0,52
Rice Fields	78,04	5,00	- 73,04	- 0,94
Grand Total	830.452,28	830.363,26		

Note: (-) indicates a decrease in area

When compared with the results of the ANN-based modeling analysis, there are notable differences in the direction of land-cover changes. In general, the Transition Matrix model projects an increase in forest area and a decrease in non-forest land-cover classes. Specifically, the Transition Matrix forecasts a forest expansion of 12,516.67 ha and an increase in shrubland of 11,680.13 ha, whereas the ANN method predicts a forest decrease of 6,127.58 ha and a significant increase in dryland agriculture mixed with shrubland of 2,672.35 ha, followed by an increase in shrubland of 5,252.72 ha.These differences reflect the fundamental characteristics of the two methods. The Transition Matrix relies on the probability of changes based on historical data between land-cover classes in an aggregated manner, without considering spatial factors such as proximity to roads, settlements, or rivers. In contrast, the ANN method utilizes deterministic spatial information to recognize more complex and contextual patterns of distribution changes. Consequently, ANN tends to produce predictions that are more spatially realistic and sensitive to unevenly distributed land pressures across the landscape.Shrubland/secondary land-use also shows striking differences, where the ANN method estimates a greater reduction compared to the Transition Matrix. This indicates that the ANN model can identify areas with high potential for conversion to more intensive land uses, such as oil palm plantations, based on surrounding environmental attributes.

Meanwhile, the Transition Matrix only captures patterns based on the frequency of previous changes, without understanding *why* changes occur at specific locations. In this context, ANN demonstrates an advantage in revealing the spatial processes behind land-use change.Therefore, the ANN-based approach offers advantages in predictive accuracy and spatial resolution, which are crucial for land-use planning, conservation, and policy evaluation, such as conservation partnerships. On the other hand, the Transition Matrix remains useful as an initial or baseline approach due to its simplicity and ability to provide a general overview of changes between land-cover classes. Using both methods complementarily can yield a more holistic and in-depth analysis to support data-driven decision-making in sustainable landscape management.These findings indicate that ANN models with deterministic variables have higher sensitivity in identifying spatially prospective locations for land clearing expansion, such as areas close to roads, settlements, and rivers. This aligns with literature suggesting that neural network-based models can learn nonlinear patterns and complex interactions among spatial variables (Glick et al., 2024).Although historical-data-based approaches such as the Transition Matrix or purely statistical methods provide a general understanding of land-cover change directions, predictive accuracy can be significantly improved by incorporating spatial-temporal drivers.

Factors such as proximity to infrastructure (roads, settlements, rivers), topography, accessibility, demographic pressure, and policy changes have been shown to strongly influence deforestation and land-use change processes (Curtis et al., 2018; Gaveau et al., 2022). Therefore, integrating these variables into models—through machine learning approaches or spatial-rule-based systems such as Artificial Neural Networks (ANN) or Random Forest—enables modeling that not only relies on past patterns but also captures the structural tendencies of ongoing and future changes (Glick et al., 2024). Incorporating spatial-temporal variables in land-use change modeling not only enhances predictive precision but also enriches the analysis with causal dimensions, making the results more relevant for spatial planning, deforestation mitigation, and sustainable landscape management (Austin et al., 2018; Meijaard et al., 2020).In the management of Gunung Leuser National Park (TNGL), challenges such as encroachment, illegal logging, wildlife hunting, land claims, and various disasters—such as floods and landslides—have been ongoing issues over the past 20 years (Wiratno, 2013). According to World Resources Institute (WRI) data, Indonesia was among the top 10 countries with the highest deforestation rates in 2018 (Kusnandar, 2019). Encroachment and plantation cultivation dominate conflicts between local communities and stakeholders. As shown in Figure 4.15, deforestation between 2023 and 2033 covers 9,447.42 ha, reforestation covers 4,833.73 ha, stable forest remains 762,403.35 ha, and stable non-forest area remains 53,159.75 ha.

Fig 5. Spatial Distribution Map of Deforestation in the TNGL Area (2023–2033)

Over the past 20 years (2003–2023), forest cover in Gunung Leuser National Park (TNGL) has declined, although it still dominates more than 90% of the area. Land conversion has primarily occurred toward mixed agriculture, plantations, grasslands, and settlements. This reduction has been driven by encroachment, plantation expansion, infrastructure development, weak law enforcement, and population growth. Although the rate of decline slowed between 2018 and 2023, pressures from non-forest activities on TNGL's ecosystems remain high, threatening its long-term sustainability.Between 2003 and 2023, TNGL experienced an average deforestation rate of 1,245.84 ha/year (0.1585%), which, while small in percentage terms, has significant ecological consequences. The pressures originate from encroachment, land clearing, logging, and development. Projections up to 2033 indicate a potential forest loss of approximately 6,127.58 ha, accompanied by increases in shrubland and mixed agriculture-shrubland cover. Reductions are also observed in plantations, grasslands, and paddy fields, while open land and settlements show an increase. Although the total area change is not drastic, the internal dynamics of land-cover change highlight a serious threat to the conservation of TNGL's ecosystems.

REFERENCES

[1] Abd. Kadir Wakka, & San Afri Awang. (2015). Strategies for accommodating community interests in the management of Bantimurung Bulusaraung National Park, South Sulawesi Province. ***Journal of Forest Policy Analysis.***

[2] Aguilar, R., Quesada, M., Ashworth, L., Herrerias-Diego, Y., & Lobo, J. (2008). Genetic consequences of habitat fragmentation in plant populations: Susceptible signals in plant traits and methodological approaches. Molecular Ecology.

[3] Badan Standardisasi Nasional (BSN). (2010). Land Cover Classification. Jakarta, Indonesia: BSN.

[4] Balai Besar Taman Nasional Gunung Leuser (BBTNGL), & WCS Indonesia Program. (2019). Monitoring Land-Cover Changes in Gunung Leuser and Surrounding Areas (2000–2017). Medan, Indonesia: BBTNGL.

[5] Balai Besar Taman Nasional Gunung Leuser (BBTNGL). (2021). Long-Term Management Plan of Gunung Leuser National Park 2021–2030, Aceh and North Sumatra Provinces. Medan, Indonesia: BBTNGL.

[6] Balai Besar Taman Nasional Gunung Leuser (BBTNGL). (2022). Strategic Plan of Gunung Leuser National Park 2020–2024. Medan, Indonesia: BBTNGL.

[7] Balai Besar Taman Nasional Gunung Leuser (BBTNGL), & WCS Indonesia Program. (2022). Forest and Land Cover Changes in Gunung Leuser National Park and Surrounding Areas (2020–2021). Medan, Indonesia: BBTNGL.

[8] Barus, B., & Wiradisastra, U. S. (2000). Geographic Information Systems. Bogor, Indonesia: Remote Sensing and Cartography Laboratory, Department of Soil Science, Faculty of Agriculture, Bogor Agricultural University.

[9] Didin Hartoyo, Putri, E. F., & Pambudi, K. S. (2020). Conservation Partnerships and the Future of Forests in Papua. Universitas Pertahanan.

[10] Direktorat Jenderal Konservasi Sumber Daya Alam dan Ekosistem. (2019). Decision of the Director General of Natural Resources and Ecosystem Conservation No. SK.193/KSDAE/SET/KSA.0/5/2019 on Zoning of Gunung Leuser National Park, Aceh and North Sumatra Provinces.

[11] Direktorat Jenderal Planologi Kehutanan dan Tata Lingkungan. (2017, November 6). Regulation of the Directorate General of Forestry Planning and Environment No. P.6/PKTL/SETDIT/KUM.1/11/2017 on Technical Guidelines for Mapping and Presentation of Environmental and Forestry Maps.

[12] Ernest Juliyanto Pandiangan. (2017). Analysis of Land-Cover/Land-Use Changes to Support the Management of Gunung Leuser National Park [Master's Thesis]. Bogor, Indonesia: Graduate School, Bogor Agricultural University.

[13] Food and Agriculture Organization of the United Nations (FAO). (2016). Map Accuracy Assessment and Area Estimation: A Practical Guide. Rome, Italy: FAO.

[14] Food and Agriculture Organization of the United Nations (FAO). (2020). Global Forest Resources Assessment 2020: Terms and Definitions. Rome, Italy: FAO.

[15] Food and Agriculture Organization of the United Nations (FAO). (2022). Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security. Rome, Italy: FAO. https://doi.org/10.4060/i2801e

[16] Ginting, R., & Rahmawaty. (2023). The analysis of land-use change of mangrove ecosystem in Langkat, North Sumatra, Indonesia. ***Journal of Environmental and Development Studies***, 4(2), 009–019.

[17] International Union for Conservation of Nature and Natural Resources (IUCN). (1984). IUCN Protected Area Management Categories. Switzerland: IUCN.

[18] International Union for Conservation of Nature and Natural Resources (IUCN). (2004). World Heritage Nomination: Tropical Rainforest Heritage of Sumatra (Indonesia), ID No. 1167. IUCN Technical Evaluation.

[19] Kementerian Kehutanan. (2014, May 28). Ministerial Decree No. SK.4039/Menhut-VII/KUH/2014 on the Designation of Part of Gunung Leuser National Park Forest Area, 205,355.14 ha, Langkat and Karo Regencies, North Sumatra Province.

[20] Kementerian Kehutanan. (2014, October 28). Ministerial Decree No. SK.6589/Menhut-VII/KUH/2014 on the Designation of Part of Gunung Leuser National Park Forest Area, 622,924.35 ha, Southwest Aceh, Southeast Aceh, South Aceh, and Gayo Lues Regencies, Aceh Province.

[21] Kementerian Lingkungan Hidup dan Kehutanan. (2015, May 26). Regulation of the Directorate General of Forestry Planning No. P.1/VII-IPSDH/2015 on Guidelines for Land-Cover Monitoring.

[22] Kementerian Lingkungan Hidup dan Kehutanan. (2017, November 6). Regulation of the Directorate General of Forestry Planning No. P.6/PKTL/SETDIT/Kum.1/11/2017 on Technical Guidelines for Mapping and Presentation of Environmental and Forestry Maps.

[23] Kementerian Lingkungan Hidup dan Kehutanan. (2018, June 6). Regulation of the Directorate General of Natural Resources and Ecosystem Conservation No. P.6/KSDAE/SET/Kum.1/6/2018 on Technical Guidelines for Conservation Partnerships in Nature Reserves and Protected Areas.

[24] Kementerian Lingkungan Hidup dan Kehutanan. (2024, April 2). Ministerial Decree No. 399/2024 on Standards for Dissemination of Thematic Geospatial Information on Environment and Forestry.

[25] Lillesand, T. M., & Kiefer, R. W. (1990). *Remote Sensing and Image Interpretation.* Translated edition. Yogyakarta, Indonesia: Gadjah Mada University Press.

[26] Ministry of Environment and Forestry (MoEF). (2020). State of Conservation Status of the World Heritage in Indonesia: Tropical Rainforest Heritage of Sumatra (N 1167).

[27] Rahmawaty. (2024). Community Perception and Participation Towards Managing the Impact of Climate Change in North Sumatra Province, Indonesia. Faculty of Forestry, Universitas Sumatera Utara.

[28] Rahmawaty. (2024). Climate Change Impact Assessment Based on Perception and Participation in Telagah *Village* [Conference Paper].

[29] Rahmawaty, Harahap, M. M., Kurniawan, H., & Rauf, A. (2021). Assessment of land-cover change over a period of five years in Deli Serdang (2014–2019). IOP Conference Series: Earth and Environmental Science. IOP Publishing.

[30] Rahmawaty, Harahap, Kurniawan, & Mandasari. (2020). DPSIR model approach to address land-use changes in Deli Serdang District, North Sumatra Province. ***IOP Conference Series: Earth and Environmental Science***. IOP Publishing.

[31] Rahmawaty, Rauf, A., & Aththorick, Alief. (2023). Prediction of Forest Cover Change and Carbon Stock for 5, 10, and 20 Years to Support Forest Planning and Sustainable Development Goals in North Sumatra. Sustainability Report, Universitas Sumatera Utara.

[32] Rahmawaty, Rauf, A., Harahap, & Kurniawan, H. (2020). Land cover change impact analysis: An integration of remote sensing, GIS, and DPSIR framework to address degraded land in Lepan Watershed, North Sumatra, Indonesia. ***Biodiversitas Journal,*** 23(6), 3000–3011.

[33] Ramadhani, J. (2014). Analysis of Deforestation and Forest Sustainability Using Scenario-Based Land Allocation Modelling: A Case Study at Gunung Leuser National Park (GLNP) in Langkat Regency, North Sumatra Province, Indonesia [Master's Thesis]. Enschede, Netherlands: Faculty of Geo-Information Science and Earth Observation, University of Twente.

[34] Suyadi, & Gaveau, D. L. A. (2006). Trends and causes of deforestation in Way Pemerihan, Bukit Barisan Selatan National Park, Lampung Barat, Indonesia. Wildlife Conservation Society – Indonesia Program.

[35] Wiratno. (2007). Returning National Park Management to the Field. Paper presented at the Workshop on Reducing Emissions from Deforestation and Degradation (REDD), Banda Aceh, October 1–2, 2007. Banda Aceh, Indonesia.