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Three Decade Forest Change in the Bakiriang Key Biodiversity Area, Eastern Sulawesi Island

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Abstract: The Bakiriang Key Biodiversity Areas (KBAs) on the island of Sulawesi are one of the global biodiversity landscapes identified for species conservation and the provision of critical habitats for endemic and rare species on the island of Sulawesi. However, these KBAs have experienced forest fragmentation due to the expansion of smallholder agriculture and large-scale plantations. Information regarding forest loss within the KBAs on Sulawesi Island remains very limited, necessitating a spatial assessment of forest loss. Therefore, in this study, we used Landsat-5 and Landsat-8-9 satellite imagery to map forest cover in 1995 and 2025. Geospatial analysis of the Landsat imagery was conducted using the Google Earth Engine (GEE) geospatial platform and the random forest classification algorithm. The results show a decrease in forest area of 9,155.16 ha, or approximately 12.56%, between 1995 and 2025, with a rate of decline reaching 305.17 ha/year (-0.42%). In terms of spatial patterns, changes in forest cover are distributed along the direction of the river toward its headwaters, with elevations reaching 160.41 ± 148.91 meters above sea level. Under the protection of the national forest policy, 5,381.10 ha of forest cover has been damaged within the Bakiriang Wildlife Reserve conservation area, leaving 5,495.67 ha of forest cover remaining by 2025. This indicates a lack of role and effectiveness of conservation areas in protecting forest cover within the Bakiriang KBAs, which shelter several endemic and rare species. Landscape rehabilitation of the Bakiriang KBAs through agroforestry systems in non-protected areas is recommended to enhance ecosystem functions for the habitats of key species within the KBAs.

Keyword: Bakiriang KBAs, Landsat, Species, Sulawesi

INTRODUCTION

Changes in tropical rainforest cover in Indonesia have a long history, dating from the 20th century to the present. Land use for both smallholder and corporate agriculture has been one of the causes of the shrinking forest area in Indonesia (Margono *et al.* 2014; Tsujino *et al.* 2016; Kelley *et al.* 2017). This trend began with the 1976–1989 transmigration program, which cleared portions of forest outside Java Island to create resettlement areas for Javanese migrants (Whitten 1987;

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Fearnside 1997). The establishment of these transmigration settlements led to the clearing of agricultural land around the resettlement areas, followed by population growth. Following Indonesia's economic crisis at the end of the 20th century, small-scale farmers were forced to exploit the forest to the fullest extent possible. Sunderlin *et al.* (2001) state that the crisis facing small-scale communities in Indonesia compelled farmers to clear forests for agricultural expansion in order to secure their long-term economic survival. Additionally, forest cover loss occurred as a result of business permits for the exploitation of natural timber for export purposes. Following timber exploitation, in the early 21st century, forest cover came under pressure due to the expansion of large-scale oil palm plantations.

Changes in forest cover have been shown to have ecological impacts on wildlife (Hill & Curran 2001; Balthazar *et al.* 2015). Habitat loss and the decline in forests' ability to provide food are among the causes of wildlife species' vulnerability. This is particularly true in Key Biodiversity Areas (KBAs), which serve as critical habitat-supporting landscapes for key species in Indonesia. KBA landscapes play a crucial role, particularly in supporting species' ranges and providing the necessary habitat complexity, thereby serving as a benchmark for landscape management aimed at species conservation. Unfortunately, KBA landscapes in Indonesia face the challenge of changes in forest cover, leading to the isolation of important, unique, rare, and endemic species. As a result, many species are at risk of losing their habitats and home ranges, and the connectivity between forest patches is being disrupted. Yang *et al.* (2024) found that approximately 57% of all KBAs worldwide have experienced fragmentation due to human activities.

Over the past several decades, changes in forest cover have been identified using spatial approaches to determine the patterns and extent of these changes (Giriraj *et al.* 2008; Suleiman *et al.* 2017; Nguyen *et al.* 2025). Spatial approaches are very useful for reducing the enormous costs associated with terrestrial surveys (Slonecker *et al.* 2010). Terrestrial surveys are typically used to validate and verify spatial forest cover data (Mengesha *et al.* 2015). Over the past five decades, satellite-based Earth observation science has advanced rapidly and has proven highly valuable for monitoring forest cover dynamics. The Landsat mission by NASA-USGS is the only satellite program providing temporal Earth observation data spanning over 50 years

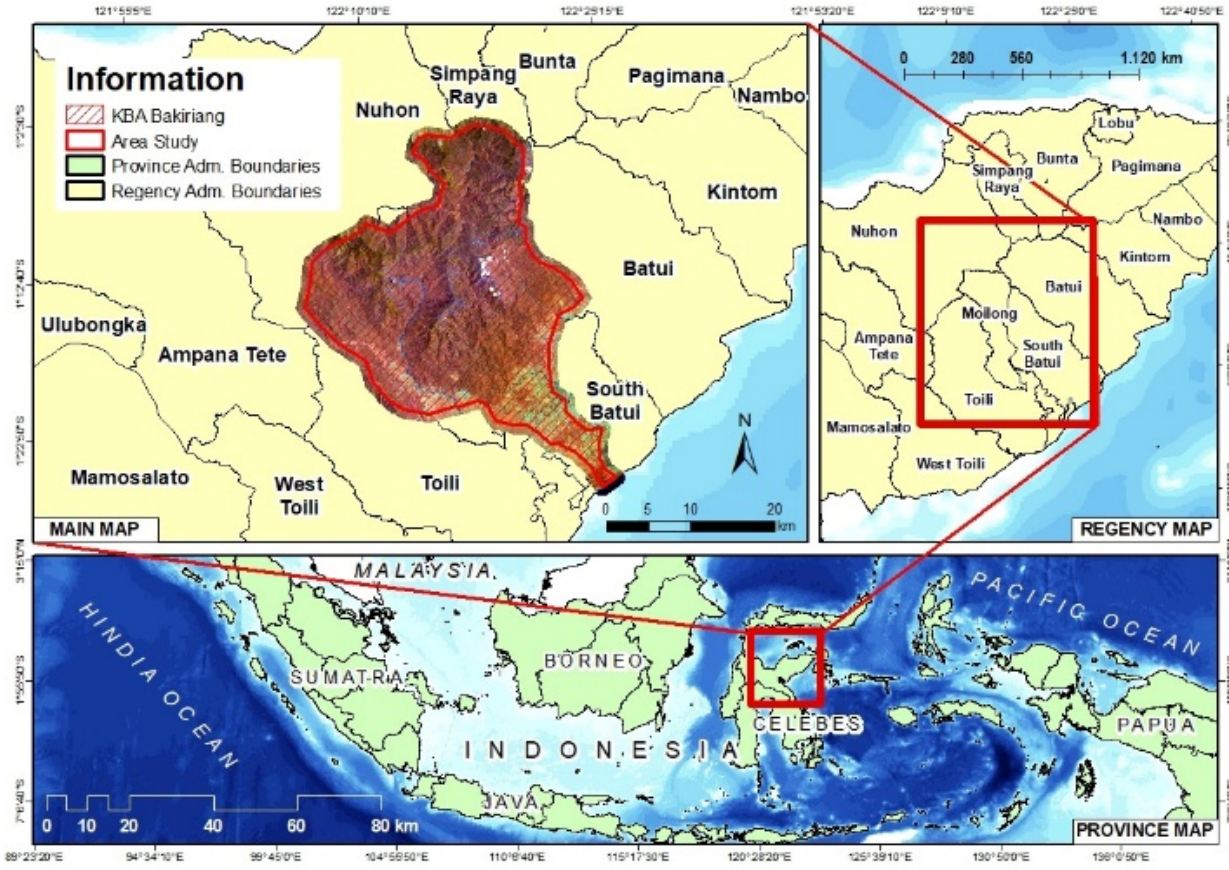


Figure 1. The map of Bakiriang KBA in Sulawesi Eastern

(Loveland & Dwyer 2012; Loveland *et al.* 2022). This spans from the first-generation Landsat satellite, Landsat-1—which has been operational since 1972—to the latest-generation Landsat satellite, Landsat-9, which began operations in 2021 (Acker *et al.* 2014; Masek *et al.* 2020; Srivastava *et al.* 2022; Eon *et al.* 2024). The temporal resolution of Landsat data makes it widely used for monitoring forest cover, dynamics, and the causes of forest degradation. For example, in a study by Potapov *et al.* (2017), Landsat archive data were used to examine changes in forest cover within intact forest landscapes (IFLs) globally from 2000 to 2013. At the local level, Landsat data is also highly valuable; for instance, Marfi *et al.* (2025) used temporal Landsat data to map mangroves in the Aceh Tamiang region of Indonesia from 2000 to 2023.

Strengthening the Bakiriang KBA requires data on forest cover, which is essential for protecting the habitats of key species. Changes in forest cover over the years are a primary indicator for assessing forest fragmentation and its implications for disrupting species' ranges within the area. Unfortunately, there is currently no information available regarding forest cover in the Bakiriang KBA. Without forest cover data, the sustainability of conservation efforts in the area is at risk. This is because forest cover data informs stakeholders' decisions regarding area management, species conservation, and the protection of key species' habitats. Therefore, this study is necessary to gather information on forest cover and the extent of fragmentation, as well as its potential impact on species habitats. This information can then be used by stakeholders within the Bakiriang KBA.

METODOLOGI

Study Area of Bakiriang KBA

The study site is located in the Key Biodiversity Area (KBA) of Bakiriang, which covers 72,376.54 ha (https://www.keybiodiversityareas.org/site/factsheet/44805). Geographically, the Bakiriang KBA is situated in the eastern part of Sulawesi Island, and administratively, it is located in Banggai Regency, Central Sulawesi Province (Figure 1). The Bakiriang KBA encompasses six districts: Batui District, South Batui District, Moilong District, Toili District, Nuhon District, and Simpang Raya District.

Data Sources and Use

Environmental Remote Sensing Data

The environmental remote sensing data used in this study include forest cover, elevation, slope, water temperature, and precipitation data. Forest cover data were obtained from forest cover estimates using Landsat satellite data. Elevation and slope data were derived from the Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM). Water temperature data were obtained from estimates provided by the Climate Hazards Center InfraRed Temperature with Stations (CHIRTS). Rainfall data were obtained from the Climate Hazards Center InfraRed Precipitation with Stations (CHIRPS). All of this environmental remote sensing data was acquired through the Google Earth Engine (GEE) platform (Gorelick *et al.* 2017) and exported in raster format for further analysis using ArcMap 10.8.

Indonesia Forest Policy Data

National policy data were used in this study to trace changes in land cover related to the level of forest protection through national policy support. Three sets of national policy data were used: the National Forest Status (FKH), the Moratorium on the Postponement of Business Permits for the Utilization of Forest Areas (PIPPIB), and the Forestry Business Area (PBPH) (Table 1). All spatial data from these national forestry policies were obtained from an open-source website—

Table 1. Data use from Indonesia government policy

Indonesia Government Policy	Indonesia Name	Abbrevation	Reference
Forest National Status	Peta Fungsi Kawasan Hutan	FKH	
Moratorium on Postponement of Business Permits for Utilization of Forest Areas	Peta Indikatif Penghentian Pemberian Izin Baru	PIPPIB	Forestry Minister Decree No. 6156 on 2025
Forestry Business Area	Perizinan Berusaha Pemanfaatan Hutan	PBPH	Environment and Forestry Minister Decree No. 7875 on 2020

the SIGAP platform operated by the Ministry of Environment and Forestry (https://sigap.kehutanan.go.id/) (KLHK 2024).

Forest Cover and Change Analysis

An analysis of habitat loss for species in the Bakiriang KBA was conducted using an approach that tracked changes in forest cover from 1995 to 2025. The forest cover analysis was performed using a satellite-based remote sensing approach. The satellite imagery used was Landsat imagery, which has a long-term temporal record spanning more than 50 years (Crawford et al. 2023). For the year 1995, Landsat-5 Thematic Mapper (TM) imagery was used. Meanwhile, for the year 2025, a combination of two images was used: Landsat-8 Operational Land Imager (OLI) – Thermal Infrared Sensor (TIRS) and Landsat-9 OLI2/TIRS2.

Approach Evaluation Analysis

To refine the analysis, an accuracy analysis is required to measure the accuracy of the remote sensing approach. The accuracy analysis was conducted using validation data obtained from the GEE platform. Validation points were determined through random sampling across three land cover classes and based on a Landsat composite layer comprising the NIR, SWIR1, and Blue bands. The accuracy analysis used the confusion matrix approach and was followed by an analysis of accuracy metrics, namely User Accuracy (UA), Producer Accuracy (PA), Overall Accuracy (OA), and Kappa Statistics (KS). These four accuracy metrics are presented in Equations 1 through 4.

$$UA = \frac{X_{ii}}{X_{i+}} \quad \text{.....(Eq. 1)}$$

$$PA = \frac{X_{ii}}{X_{+i}} \quad \text{.....(Eq. 2)}$$

$$OA = \frac{1}{N}\sum_{i=1}^{r} X_{ii} \times 100\% \quad \text{.....(Eq. 3)}$$

$$KS = \frac{N\sum_{i=1}^{r} X_{ii} - \sum_{i=1}^{r} X_{ii}(X_{i+} \times X_{+i})}{N^2 \sum_{i=1}^{r} X_{ii}(X_{i+} \times X_{+i})} \quad \text{.....(Eq. 4)}$$

$$X = \frac{x}{X} \quad \text{.....(F1)}$$

Information :

UA	= User's Accuracy
PA	= Producer's Accuracy
OA	= Overall Accuracy
KS	= Kappa Statistic
X_{ii}	= Number of corrected classified samples of class i
X_{i+}	= Total number of samples classified as class i (row total)
X_{+i}	= Total number of reference samples of class i (column total)

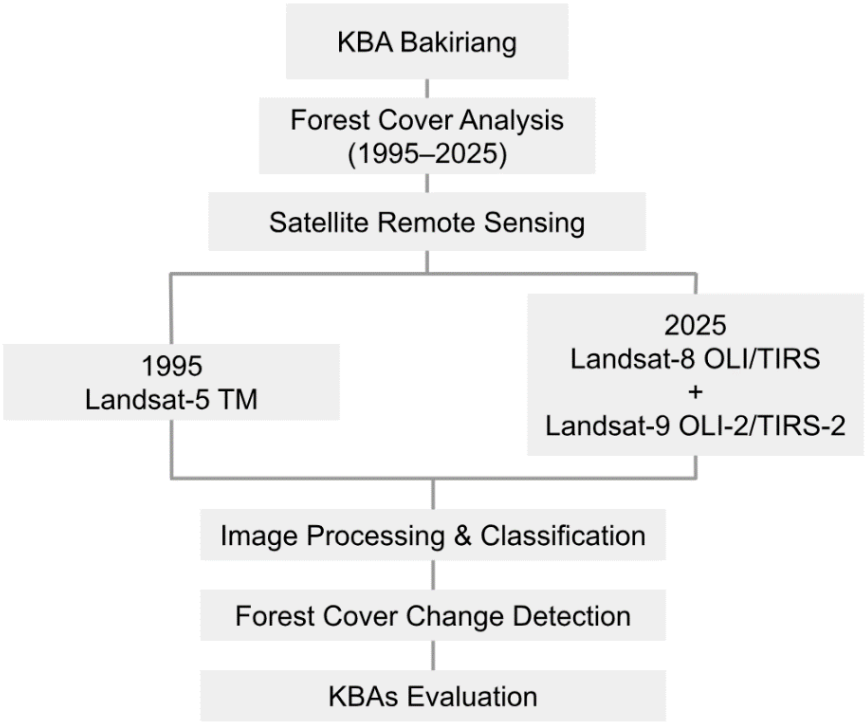


Figure 2. The flowchart of forest cover analysis

RESULTS AND DISCUSSION

Spatial Characteristics of Bakiriang KBA

The Bakiriang KBA is located in a coastal area, with a small portion extending into the mountainous region. Topographically, based on SRTM DEM data, the mountainous section to the northwest of the Bakiriang KBA reaches an elevation of 2,226 m above sea level (Figure 3; Table 2). The topography of this coastal-mountainous area features slopes ranging from 0 to 75.97%. Climatically, the Bakiriang KBA area exhibits equatorial rainfall characteristics, with annual precipitation ranging from 1,670 to 2,539 mm/year (Figure 4; Table 2). Based on CHIRTS data, this climate results in air temperatures ranging from 24.92 to 32.26°C, with the coldest areas located at elevations above 2,000 msl.

Forest Cover Change in Bakiriang KBA

The random forest machine learning algorithm successfully mapped changes in forest cover in the Bakiriang KBA. In 1995, the forest area totaled 71,619.30 ha, or approximately 98.27% of the Bakiriang KBA's total area. This forest cover changed by 2025, showing a decrease in forest area of 9,155.16 ha, or 12.56%, leaving a remaining forest area of 62,464.14 ha.

Conversely, there was an increase in non-forest cover area of 9,139.77 ha, or about 12.54%, caused by the expansion of agriculture and settlements. The annual rate of forest area loss was 305.17 ha/year (-0.42%), while the annual rate of non-forest area increase was 304.66 ha/year (+0.42%). The decline in forest area observed in this study is higher than the regional average for the island of Sulawesi. According to a study by Supriatna *et al.* (2020), deforestation in Central Sulawesi Province between 2000 and 2017 reached 11.04% or 737,516 ha. Meanwhile, at the Sulawesi Island level, these findings are higher than those reported in the study by Voigt *et al.* (2021), which recorded a 2.17% decrease in forest area between 2000 and 2018. However, the deforestation detected in the Sulawesi Island region is lower than that in Sumatra, which experienced the most severe decline in forest area, reaching 49.85% or approximately 1,844,804.3 ha between 2000 and 2012 (Supriatna *et al.* 2017).

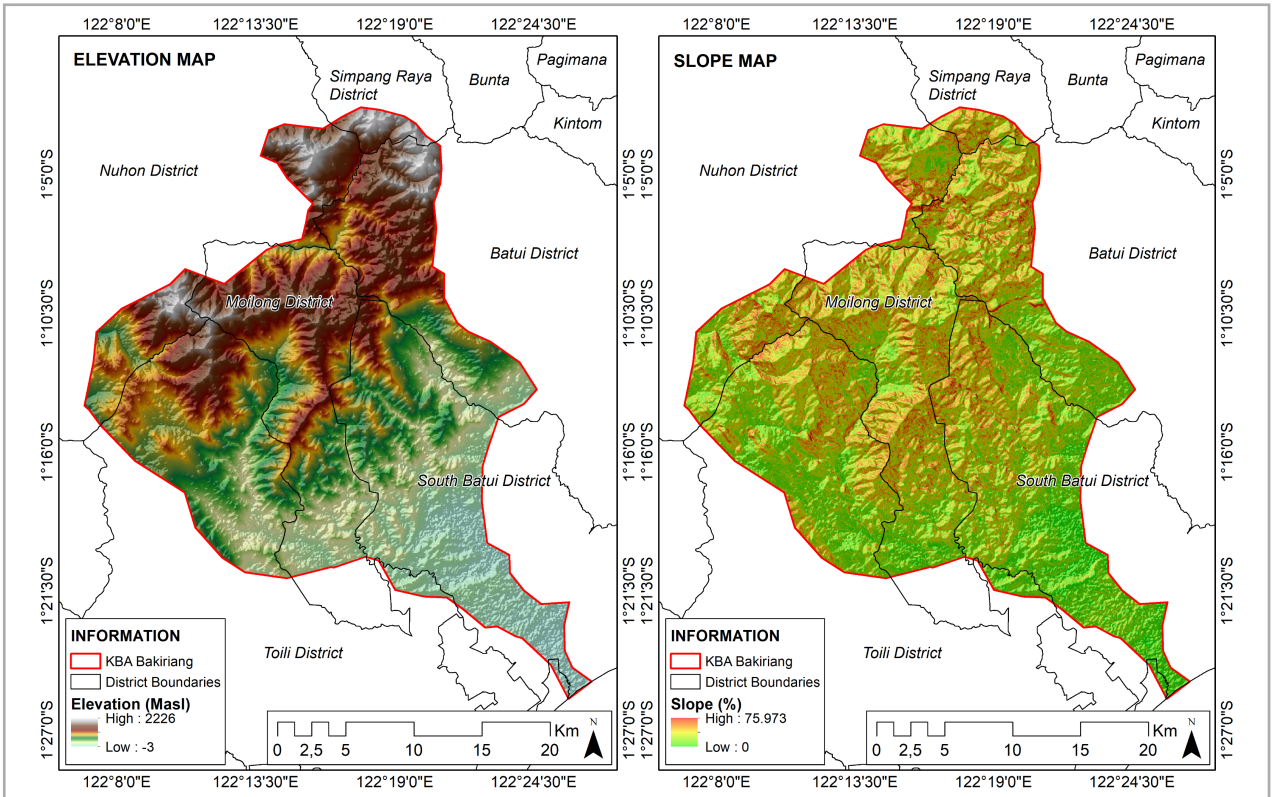


Figure 3. Spatial of elevation and slope factor of KBA Bakiriang

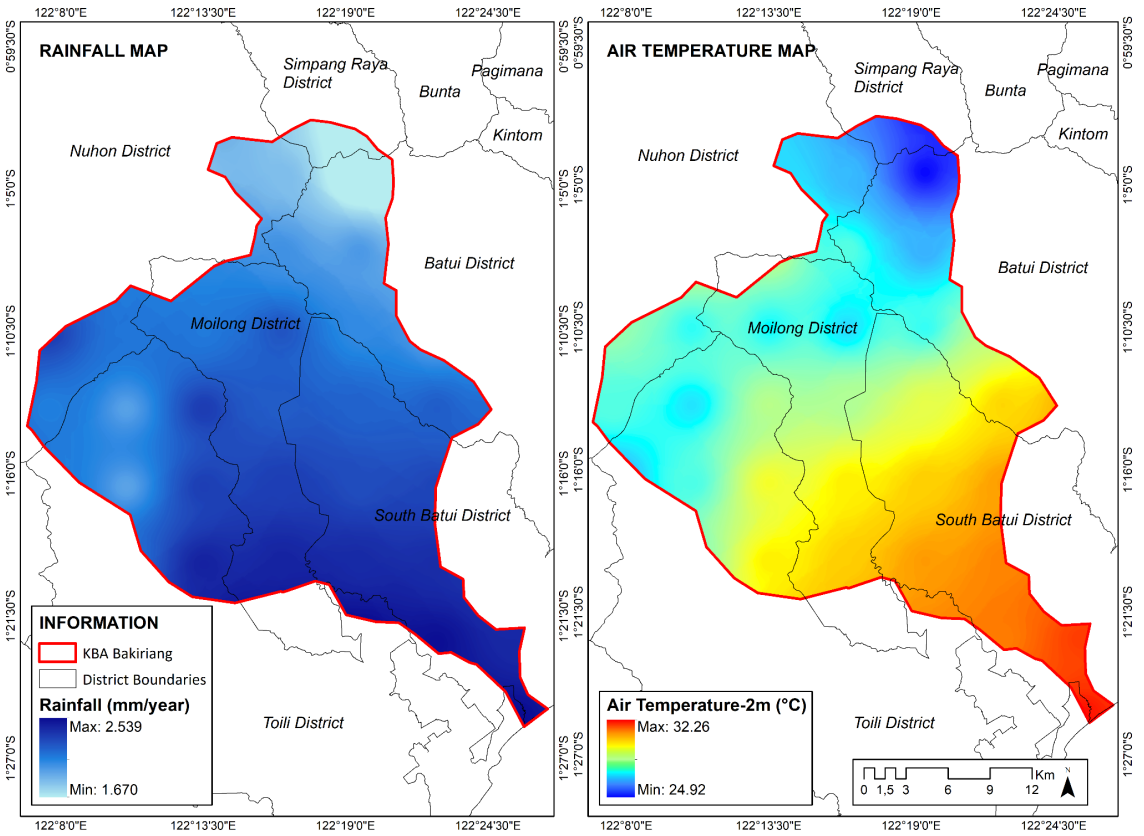


Figure 4. Spatial of climate factor of KBA Bakiriang

Table 2. Statistically of environmental factor for KBA Bakiriang

Environmental parameter	Mean ± SD	Min - Max
Elevation (msl)	814.456 ± 537.796	-3.00 - 2,226.00
Slope (%)	20.889 ± 11.047	0 - 75.97
Rainfall (mm/years)	2,261.00 ± 195.44	1,670.00 - 2,539.00
Air temperature (°C)	29.32 ± 2.03	24.92 - 32.26

The pattern of non-forest area expansion within forest areas follows the course of the upstream river up to an elevation of 160.41 ± 148.91 m above sea level, or 0 m above sea level to 2,197.00 m above sea level (Figure 6). Rivers serve as a vital water source for small-scale agricultural activities and as local transportation routes (Mei et al. 2025; Tong 2023). Additionally, the Bakiriang KBAs feature mountainous topography, leading farmers to prioritize land clearing in areas near rivers rather than in mountainous regions where land resource management is hindered by limited accessibility. This is evident from the overlay of the river network with areas of forest degradation in Figure 6. Forest degradation occurs along 654.25 km of river streams, consisting of 3 main rivers totaling 70.55 km and 583.70 km of tributaries.

In addition to physical land characteristics, climatic factors also influence farmers' preferences when seeking land within forested landscapes. High rainfall is essential for agricultural crop cultivation and determines land productivity; consequently, farmers' acquisition of forest land tends to follow landscapes with high rainfall levels (Ketterings *et al.* 1999; Jonah & Kalifi 2017; Desbureaux & Damania 2018). Based on an overlay with climate data, forest cover change occurred in the Bakiriang KBAs with an annual rainfall of 2,430 ± 82.73 mm/year, or 1,807 mm/year to 2,538

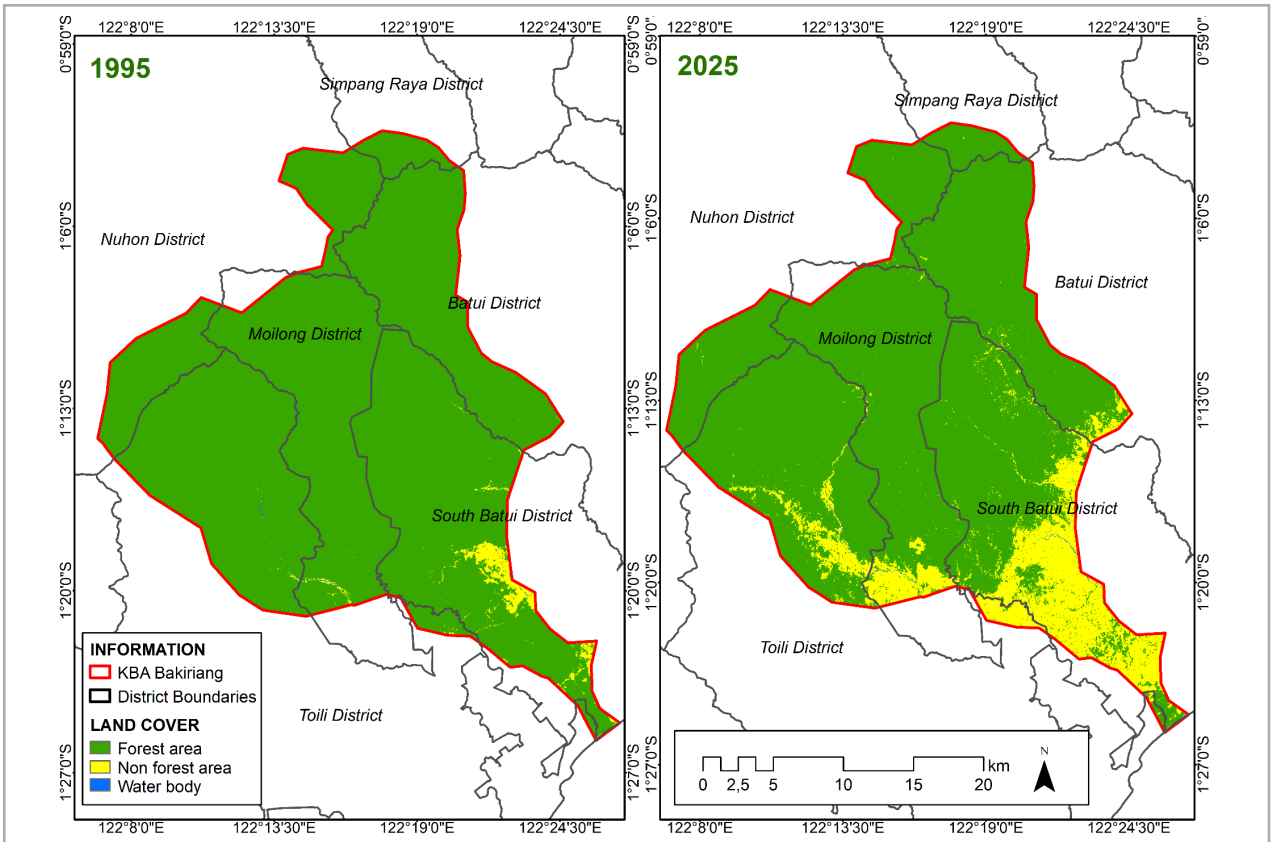


Figure 5. Spatial distribution of forest cover in 1995 and 2025

mm/year. As for air temperature, forest cover changes are spatially distributed at 30.72 ± 0.87°C, or 25.75°C–32.25°C. Conversely, the conversion of forest land to agricultural use in landscapes with high rainfall will result in severe erosion and trigger flooding. This is due to the absence of vegetation cover, which reduces canopy interception and runoff retention (Guzha *et al.* 2018). Furthermore, the absence of vegetation cover causes soil pores to shrink, making it difficult for the soil to absorb water and thereby increasing runoff (Sahani & Behera 2001; Davari *et al.* 2020). High runoff is followed by erosion and leads to deterioration in river water quality, which is considered to have the potential to eliminate habitats for freshwater fish and freshwater insects in the Bakiriang KBAs (Mol & Ouboter 2004; Wantzen & Mol 2013; Pelicice *et al.* 2021; Rufino *et al.* 2025). The destruction of freshwater fish and freshwater insect habitats in these KBAs will lead to a decline in their populations, thereby disrupting food webs and resulting in a reduction in food availability for fauna that rely directly on aquatic food resources, such as kingfishers and others. Long-term forest loss due to forest conversion in high-rainfall areas will lead to reduced rainfall in the future, significant shortening of the wet season, thereby affecting agricultural productivity (Arias et al. 2018; Leite-Filho *et al.* 2021; Smith *et al.* 2023). Furthermore, deforestation also contributes to a reduction in water storage, causing rivers to dry up during the dry season (Panday et al. 2015; Coe et al. 2021; Zhang and Wei 2021). Declining productivity will continue to drive farmers to clear new land, and indirectly, this pattern of forest destruction will repeat itself.

Table 3. Statistically of forest cover change

Land cover	1995 (ha and %)	2025 (ha and %)	Change
Forest area	71619.30 (98.27%)	62464.14 (85.71%)	-9155.16 (-12.56%)
Non forest area	1190.16 (1.63%)	10329.93 (14.17%)	+9139.77 (+12.54%)
Water body	70.83 (0.10%)	86.22 (0.12%)	+15,39 (+0.02%)

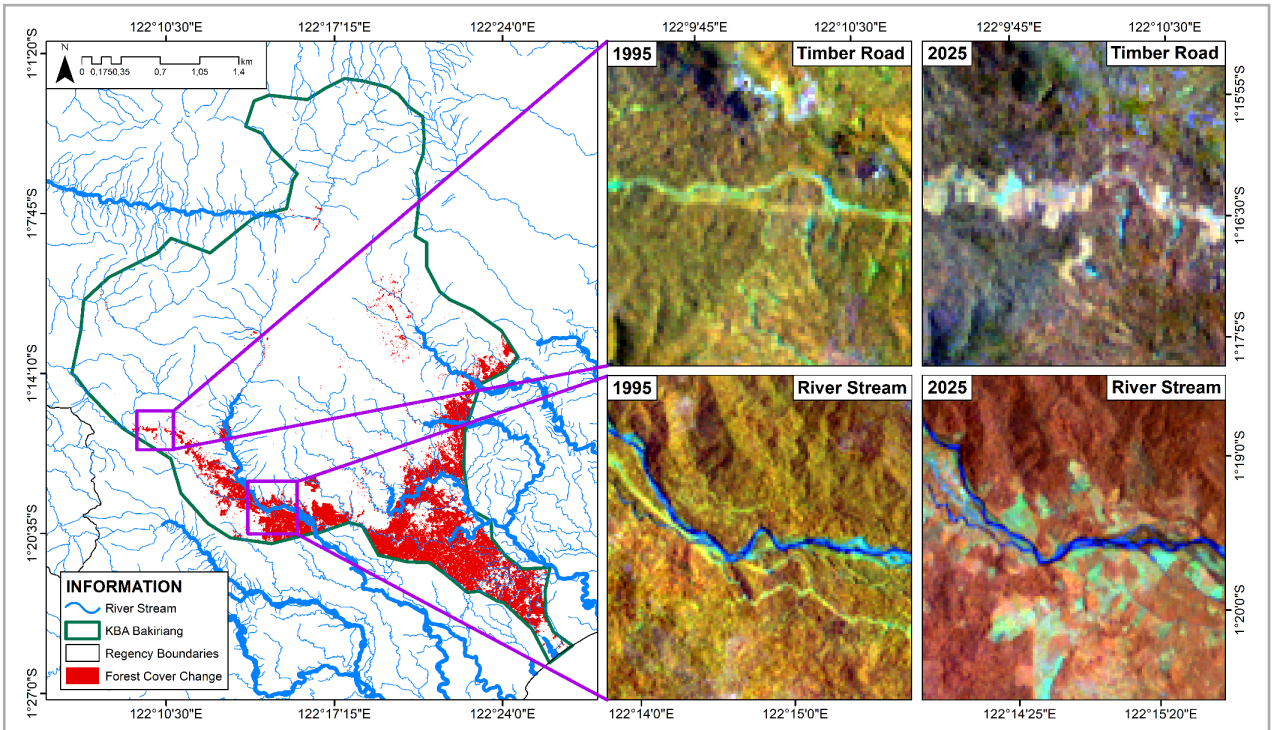


Figure 6. Spatial distribution of forest cover change based on river stream

Forest Cover Change Under National Forestry Status

In terms of forest governance in Indonesia, the Bakiriang KBA is classified as a forest area covering 69,374.16 ha (Figure 7). Under the latest policy regarding forest area protection—the PIPPIB policy—25,104.56 ha are covered. Spatially, the area protected under the PIPPIB policy has a forest cover of only 19,779.93 ha, or approximately 78.79%, while the remaining 5,498.28 ha has been degraded (Table 4). Furthermore, the conservation forest policy within the Bakiriang Wildlife Reserve has not been immune to forest degradation. According to the mapping conducted, the remaining forest area within the Bakiriang Wildlife Sanctuary will total only 5,495.67 ha by 2025, while the remaining 5,381.10 ha has been converted to non-forest land (Figure 5; Figure 7). This indicates that the effectiveness of conservation forest management has not been optimal in protecting forest cover. A similar situation occurs in the Rema-Kalenga Wildlife Sanctuary in Bangladesh, which has a forest loss rate of 0.43% caused by the conversion of forest land into smallholder agriculture (Hossain & Numata 2021). Meanwhile, in Indonesia, the conservation forest area within Gunung Palung National Park in Kalimantan is experiencing forest loss at a rate of 112 ha per year (Fawzi *et al.* 2018). Forest loss in conservation forest areas is driven by the desire of local communities to gain control over land resources within these areas. This also occurs in Bangladesh, where approximately 45% of households are identified as drivers of deforestation around the Teknaf Wildlife Sanctuary (Ullah *et al.* 2022). Inequalities in farmers' land assets and poverty levels are the root causes of land extraction in conservation areas (Vedeld *et al.* 2012; Damnyag *et al.* 2013). Although some conservation areas possess natural assets that can provide livelihoods for local communities, community-based conservation management remains a crucial and challenging issue. A

Table 4. Statistically forest cover in 2025 based on forest national policy

Land cover	KH-HPT	KH-HPK	KH-HL	KH-HK	PIPPIB	PBPH
Forest area	39125.79	6275,7	11267,91	5495,67	19779,93	32897,70
Non forest area	750.87	1521,09	27,36	5381,10	5498,28	15,21
Water body	18.00	20,07	0	16,56	16,56	372,69

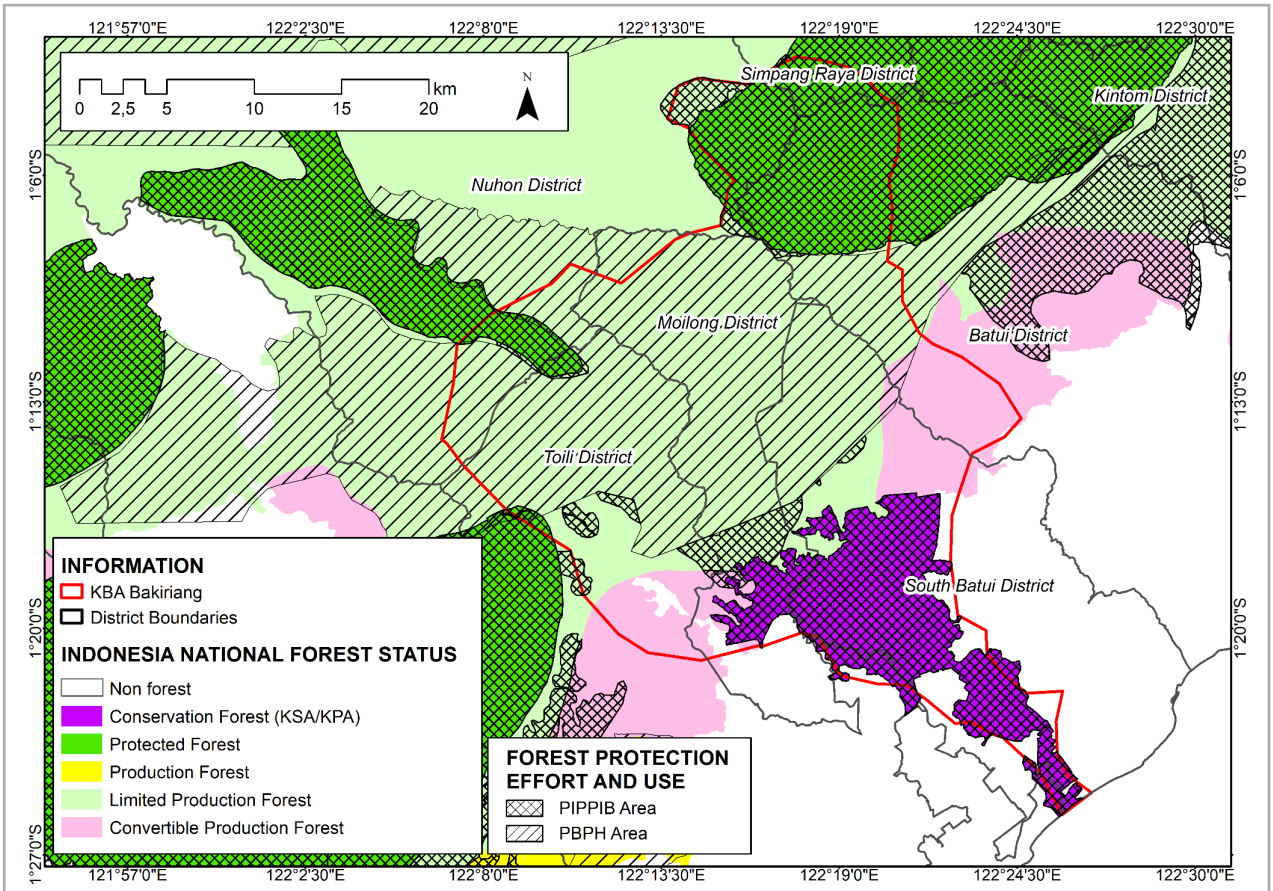


Figure 7. The Indonesia forestry policy for forest management, forest protection effort, and forest use

win-win solution that balances ecosystem conservation and poverty reduction around conservation areas requires innovative approaches that avoid displacing or creating conflict with impoverished communities while simultaneously minimizing potential impacts on the biodiversity within these areas (Cernea & Schmidt-Soltau 2006; Ferraro & Hanauer 2011; Oldekop *et al.* 2019). In addition to forest areas designated for conservation, production forests are also located within the Bakiriang KBAs. Within these KBAs, there are production forest areas designated for timber harvesting (PBPH) covering 33,038.39 ha. According to national data on the Ministry of Forestry's SIGAP platform, the company engaged in natural timber harvesting is PT Bina Balantak Raya, which has held a timber harvesting permit from the Indonesian government since 2004, under permit number 334/Menhut-II/2004 (https://petahutan.fwi.or.id/web/entity/read/hph/222).

In addition to national policies regarding forest areas, national policies related to the allocation of economic roads connecting different regions also affect ecosystem cycles due to the loss of tree cover. In this case, the connecting road bisects the Bakiriang KBA and, worse still, bisects the Bakiriang Wildlife Sanctuary, which has the status of a conservation forest. The presence of this road is also considered to potentially facilitate community access to forest lands and encourage illegal logging and land-use conversion. Additionally, research by Healey *et al.* (2020) reports that the presence of a road bisecting the Rawa Aopa Watumohai National Park in Southeast Sulawesi Province has led to the death of individuals of various species. In this case, the construction of a timber haulage road by a timber company within a production forest area (KH-HPT) has also contributed to forest degradation (Figure 6). The expansion of smallholder agriculture and plantations in the areas surrounding the timber road resulted from a lack of oversight of the forest areas after the timber company ceased operations. The combined effects of logging and a lack of oversight of agricultural activities have led to uncontrolled deforestation (Brandt *et al.* 2016; Tegegne *et al.* 2016; Jonah & Kalifi 2017; Karsenty & Hardin 2017). Therefore, policy support for controlling deforestation is essential to limit the conversion of forests into non-forest areas. In particular, consistency in national policy is crucial to prevent changes in the designated status of forest areas—from forest to non-

forest—within the Bakiriang KBAs. This is similar to what occurred on the island of Kalimantan between 2000 and 2010, where changes in policies regarding the functional status (classification) of forest areas led to deforestation (Gaveau *et al.* 2013).

Implication of Forest Cover Change to Biodiversity

Changes in forest cover have become a major issue in Asia, particularly on the island of Sulawesi, where they threaten endemic species (O'Brien & Kinnaird 1996). The implications of these changes for species and their habitats are of critical importance. Indications of forest fragmentation from the results of this study show that the Bakiriang KBA area is divided into two parts: the majority of the montane forest remains relatively intact, while a small portion of forest is located in the coastal area (the Bakiriang Wildlife Reserve section) (Figure 5; Figure 7). In the montane forest section, there are corporate activities involving the logging of natural timber for timber export. Meanwhile, in the southeastern section—which is at a lower elevation—severe fragmentation has occurred due to the expansion of smallholder agriculture (cocoa, corn, etc.) and oil palm plantations, which are believed to be disrupting habitats suitable for the home ranges of mammal species undergoing local migration. In particular, the area faces pressure from the expansion of smallholder cocoa landscapes in Central Sulawesi, which serve as a livelihood for rural farmers (Clough *et al.* 2010).

Macrocephalon maleo is one of the resident species of the Bakiriang Wildlife Reserve (Dekker 1990). In addition, there are mammal species—namely the Sulawesi babirusa and the anoa—that are endemic to the region and inhabit the montane forests of Sulawesi Island (Patry *et al.* 1995; Burton *et al.* 2005; Rozzi 2017). Therefore, forest cover is crucial for supporting the Maleo's habitat. Complex forest cover can provide a diverse food supply for the Maleo bird; thus, forest degradation will lead to a decline in the species' population. This is characterized by the species migrating to unsuitable areas, which intensifies competition for food sources and ultimately results in the species' extinction due to an inability to adapt. Crooks *et al.* (2017) state that forest fragmentation, which leads to habitat loss, contributes to high rates of extinction among terrestrial mammals globally. Specifically in the southeastern coastal region of Banggai Regency, deforestation or forest fragmentation threatens primate species (Supriatna *et al.* 2020).

According to GBIF data compiled in 2025, the species *M. maleo* has not yet been detected within the Bakiriang KBA landscape. This contradicts the species record justification by Dekker (1990), who found that the Bakiriang area is one of the Maleo species hotspots. In addition, reports from several local news outlets have also documented the presence of the Maleo species and identified the Bakiriang KBA as the last bastion of forest cover along the southeastern coast of Banggai Regency. In addition to the Maleo, there are also several rare species found in Banggai Regency and its surrounding areas, namely Ailurops ursinus, Bubalus depressicornis, Bubalus quarlesi, Macaca tonkeana, Strigocuscus celebensis, and Tarsius tarsier (Figure 8). These fauna species have not yet been detected in the Bakiriang KBA, thus requiring confirmation to underscore the urgency of managing conservation areas that harbor rare and endemic species. For example, as noted in the study by Burton *et al.* (2005), the Sulawesi Anoa in the mountainous region of Banggai is still classified as having an "unconfirmed presence."

Recommendation for Bakiriang KBA Conservation Efforts

Forest area management supported by intensive protection policies is essential for the preservation of the Bakiriang Wildlife Sanctuary as part of a key biodiversity area (KBA). This is because forest degradation has occurred due to a lack of attention and protection against environmental crimes, such as land conversion for oil palm plantations and smallholder agriculture. A species inventory is also needed within the Bakiriang KBA to enhance conservation value and prevent the extinction of local species due to the absence of baseline data. This is particularly true for species with specific preferences regarding microclimate conditions, water quality, and ecological interactions with other species. Cross-sectoral collaboration at the national, regional, and local levels is essential to improve the effectiveness of conservation management in the Bakiriang KBA and the Bakiriang Wildlife Sanctuary. Furthermore, area protection is also essential for safeguarding the Maleo bird as a Cultural Keystone Species for the Batui indigenous community. Therefore, community-based species conservation is crucial to mitigate land conflicts that frequently occur in protected forest areas across Indonesia (Riley 2002; Kusters *et al.* 2007.).

Collaboration at the site level through the implementation of agroforestry innovations serves as a middle ground for the rehabilitation of the degraded

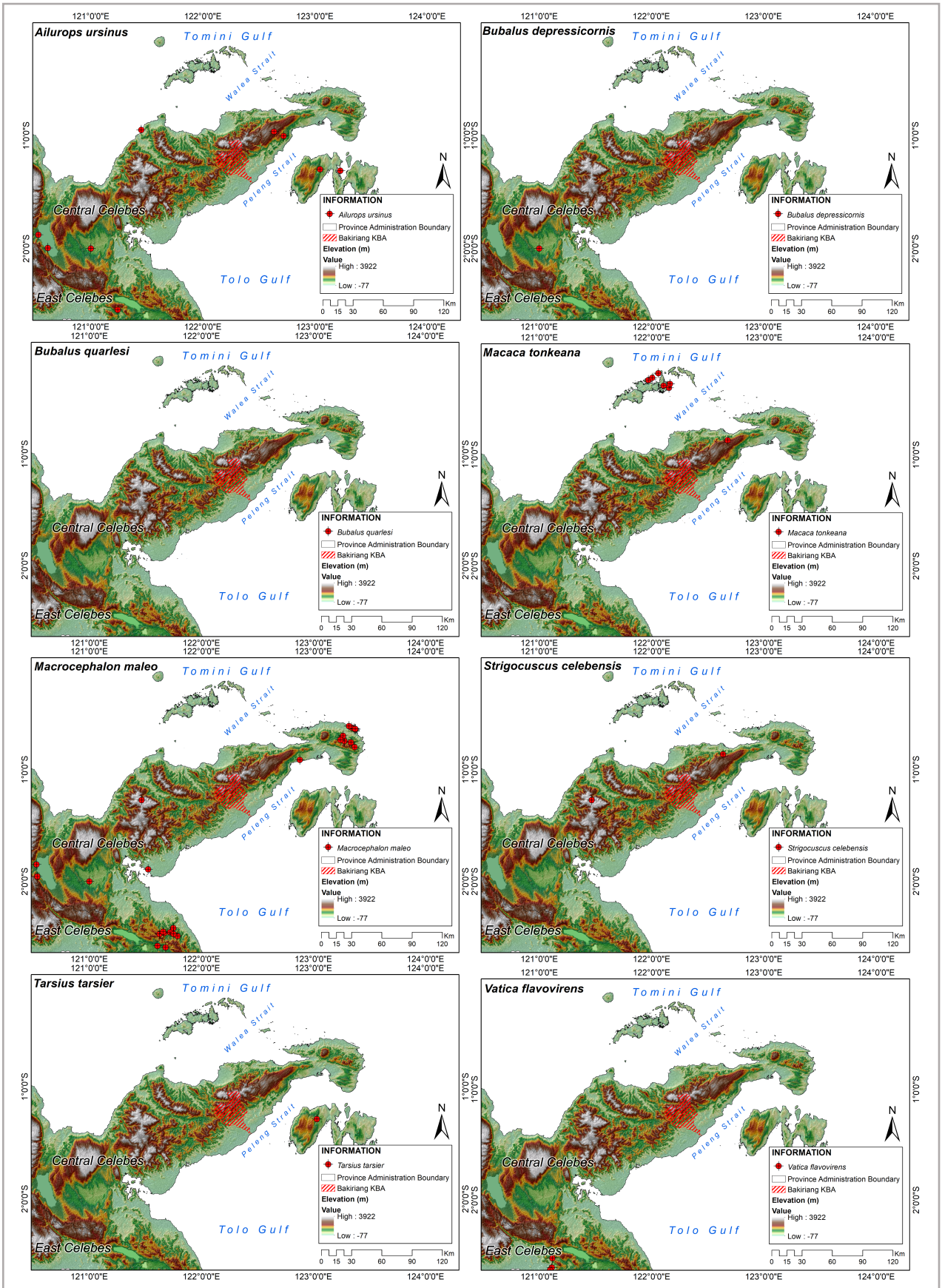


Figure 8. Species distribution for key species of Bakiriang KBA using GBIF report

Bakiriang KBA landscape. Agroforestry is considered a middle ground for maintaining access to land-use resources within KBAs while still utilizing rare tree species as the canopy (van Noordwijk *et al.* 2020; Kokou *et al.* 2024; Beatty *et al.* 2018). Key flora species, particularly tree species, can serve as options in agroforestry implementation, thereby aiding the conservation of rare and endemic tree species in Sulawesi. For example, *Hopea celebica* and *Vatica flavovirens* are trees that produce timber for domestic production and export. In addition, wildfruit tree species can also be used in agroforestry systems to provide food for bird species (Styger *et al.* 1999; Fentahun & Hager 2010; Yashmita-Ulman *et al.* 2018; Suwardi *et al.* 2025; Sharma *et al.* 2025). Increased tree diversity in agroforestry is also considered capable of reducing the potential for runoff and erosion, thereby indirectly improving water quality (Zhu *et al.* 2020; Delgado-Lemus & Moreno-Calles 2022; Salceda-Gonzalez *et al.* 2024). This is expected to enhance the river's ecosystem functions in providing habitat for endemic freshwater fish species found within the Bakiriang KBAs.

Evaluation of Methodological and Limitation

In the detection of forest cover in the Bakiriang KBAs, accuracy levels differed between 1995 and 2025. Based on accuracy test data from 169 points in 2025, the accuracy obtained from modeling using the random forest algorithm reached 0.85 (overall accuracy) and 0.75 (kappa statistics). Meanwhile, forest cover classification in 1995, using 113 validation data points, had a higher accuracy rate, reaching 0.95 (overall accuracy) and 0.92 (Kappa statistic). This difference is believed to be due to the fact that forest cover heterogeneity in 2025 is higher than in 1995, thereby increasing the level of bias in the random forest classification process. This is caused by greater variation in tree density, which leads to a wider standard deviation in the derived indices from Landsat satellite data, thereby increasing the risk of misclassifying forest cover (Tran et al. 2014; Berhane et al. 2019; Bueno et al. 2023).

CONCLUSIONS

Changes in forest cover have put pressure on the Bakiriang KBAs, resulting in the fragmentation of the area, which has impacted the availability of wildlife habitat. Based on mapping using Landsat satellite imagery, forest loss reached 9,155.16 ha, or 12.56%, between 1995 and 2025, leaving approximately 62,464.14 ha of forest cover in the Bakiriang KBAs. The rate of forest cover loss reached 305.17 ha/year (-0.42%). Spatially, forest cover change is distributed along the river's course toward the upstream area up to an elevation of 160.41 ± 148.91 m above sea level. In terms of climate, forest cover change correlates with annual rainfall of 2,430 ± 82.73 mm/year. In terms of national forest policy, the changes in forest cover are largely concentrated within conservation areas, specifically the Bakiriang Wildlife Sanctuary, which spans 5,381.10 ha, leaving a remaining forest cover of 5,495.67 ha by 2025. This forest degradation indicates a lack of effective forest protection within conservation areas. This is considered a threat to the endemic bird species *Macrocephalon maleo* and several other rare species. Conservation efforts in the Bakiriang KBA should prioritize strengthened forest protection, baseline species inventories, cross-sectoral collaboration, and community-based conservation. Landscape management innovations in the Bakiriang KBA area are urgently needed to enhance the area's function in providing habitat for its key species. Agroforestry systems are also recommended for managing the KBA landscape outside protected areas to curb the rate of land degradation.

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