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Linking Forest-Area Conversion And Land-Cover Change In Central Sulawesi Grand Forest Park

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ABSTRACT

Studies on forest-area conversion generally examine land-cover dynamics and forest policy separately, leaving the relationship between formal changes in forest designation, actual landscape conditions, and their underlying institutional factors insufficiently understood. This study addresses this gap by integrating multi-temporal land-cover classification with policy, regulatory, and interview analyses to evaluate the conversion of part of the Central Sulawesi Grand Forest Park (Tahura). Sentinel-2 imagery from 2019, 2020, and 2025 was classified using the Random Forest algorithm on the Google Earth Engine platform. The spatial findings were complemented by document analysis and semi-structured interviews with three key informants from relevant forestry institutions. Classification performance showed Overall Accuracy values of 92.99%, 89.77%, and 95.30%, with Kappa coefficients of 0.8855, 0.81, and 0.86 for 2019, 2020, and 2025, respectively. The results indicate that the Tahura area decreased from 7,128 ha to 5,149 ha following Minister of Environment and Forestry Decree No. SK.6624/MENLHK-PKTL/KUH/PLA.2/10/2021. The converted area comprised 1,933 ha designated as Limited Production Forest and 46 ha as Other Land Use Areas. In 2025, the remaining Tahura was dominated by primary forest covering 3,105.38 ha (60.31%) and secondary forest covering 1,040.47 ha (20.21%). Although the conversion complied with formal procedures, it revealed tensions between regional development interests and conservation objectives. The novelty of this study lies in linking legally mandated forest-area conversion with empirically observed land-cover dynamics and institutional explanations within a single analytical framework. Practically, the findings provide a basis for post-conversion monitoring, rehabilitation prioritization, spatial-policy evaluation, tenure-conflict resolution, and the protection of ecologically important areas.

Keywords: Central Sulawesi Grand Forest Park, forest-area conversion, land-cover change, Random Forest, Google Earth Engine, spatial policy.

1. INTRODUCE

Forests and land cover play essential roles in maintaining ecological balance, regulating climate, and providing environmental services that support human life. Forests function as carbon sinks that contribute to reducing greenhouse gas concentrations while also providing habitats for diverse flora and fauna (FAO, 2018). Land cover, including natural forests, agricultural land, and other vegetation types, influences hydrological cycles, air quality, soil stability, and disaster risk. Consequently, uncontrolled land-cover changes caused by deforestation, forest encroachment, and

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land-use conversion may result in environmental degradation, biodiversity loss, erosion, flooding, and landslides.

The Central Sulawesi Grand Forest Park, locally known as *Taman Hutan Raya Sulawesi Tengah* or Tahura Central Sulawesi, is a nature conservation area situated across Palu City and Sigi Regency, Central Sulawesi Province. The area was formally designated through Minister of Forestry Decree No. 24/Kpts-II/1999, covering approximately 7,128 ha. It was established through the integration of the Poboya Nature Reserve, the Paneki Protection Forest, and the Kapopo Nature Recreation Park (Rafiuddin & Abdur Rauf, 2023). Due to its location near urban and rural settlements, Tahura Central Sulawesi has a strategic role in maintaining the ecological stability of Palu City and its surrounding areas while also providing direct ecological and economic benefits to adjacent communities.

The forest ecosystems within Tahura Central Sulawesi support rainfall infiltration, water storage, erosion control, and the reduction of flood and landslide risks. The area also provides habitats for protected and endemic flora and fauna, including Sulawesi ebony, and therefore contributes to biodiversity conservation and the prevention of species extinction. Its ecological characteristics and strategic location also provide opportunities for ecotourism, environmental education, and scientific research.

In addition to its ecological importance, Tahura Central Sulawesi supports the livelihoods of surrounding communities. Timber and non-timber forest products, as well as environmental services associated with ecotourism, may contribute to local economic development (Budiandrian et al., 2011). Communities living in villages and urban administrative areas bordering the forest commonly use firewood as a household energy source and collect non-timber forest products, such as rattan and bamboo, for subsistence and income generation (Lahandu, 2007). These conditions demonstrate that the forest is not only an ecological asset but also an integral component of the local socioeconomic system.

However, the high dependence of surrounding communities on forest resources has also created considerable pressure on the conservation area. Activities such as timber theft, forest encroachment for agricultural and plantation development, settlement expansion, and illegal mining have occurred within and around Tahura Central Sulawesi. Such activities are generally driven by economic limitations, restricted access to education and employment, and the need to meet daily household requirements. Lewerissa et al. (2015) explained that communities living near forests often depend on forest resources for both direct consumption and commercial purposes.

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This dependence may generate conflicts between the government, as the formal manager of the forest area, and communities that have historically occupied or used land within the forest.

Tenure and settlement issues are particularly evident in Tompu Hamlet, Ngatabaru Village, Sigi Regency. Residential buildings, public facilities, gardens, and agricultural land have developed around and partly within the Tahura area. The presence of these activities reflects intensive and long-standing interactions between local communities and the forest landscape. It also indicates that the management of Tahura Central Sulawesi cannot be separated from the social history, livelihood requirements, and spatial needs of communities that may have occupied or utilized the area before its formal designation as a conservation area.

Land clearing and intensive resource utilization within forest areas may alter land-cover composition and reduce the ability of ecosystems to provide environmental services. Continuous conversion of forested land into agricultural areas, settlements, open land, or mining sites may lead to vegetation degradation, habitat fragmentation, and declining watershed-protection functions. Although forest cover may increase again through restoration or natural regeneration, the resulting vegetation cannot necessarily restore the original structure, biodiversity, and ecological functions of primary dryland forest (Chazdon, 2014). Therefore, land-cover change should be assessed not only according to changes in area but also according to the ecological quality and function of the resulting land-cover classes.

Land-cover changes may also be associated with changes in the legal functions of forest areas. Forests previously designated for conservation or protection may be reclassified as production forests or non-forest areas, thereby changing their management objectives and permitted forms of utilization. Part of Tahura Central Sulawesi has been reclassified as Limited Production Forest, a forest category that permits restricted resource use while requiring environmental sustainability to be maintained. This functional conversion reflects adjustments to spatial planning and regional development needs, including infrastructure provision, settlement expansion, and economic activities requiring more intensive land use.

Preliminary interpretation of satellite imagery indicates land clearing associated with mining activities near Poboya Urban Village. A mining company operating in this area has obtained a Forest Area Use Approval within land currently designated as Limited Production Forest. Before the functional conversion, part of this location was included within Tahura Central Sulawesi. The change was subsequently reflected in the development map of forest-area designation in Central Sulawesi Province and Minister of Environment and Forestry Decree No.

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SK.6624/MENLHK-PKTL/KUH/PLA.2/10/2021. Although forest-function conversion may accommodate regional development and economic investment, it may reduce the level of legal protection and increase pressure on biodiversity, water-catchment areas, and local microclimatic regulation.

The conversion of forest functions should therefore not be interpreted solely as an administrative consequence of spatial-planning policy. It may also represent an attempt to address long-standing tenure disputes, settlement needs, and land-use practices. Chamdani (2021) stated that forest tenure conflicts commonly arise from differences between state claims over forest areas and community control or utilization that has continued across generations. In Tahura Central Sulawesi, the conversion process reflects complex interactions among conservation objectives, regional economic interests, mining activities, settlement requirements, community land claims, and the biophysical condition of the forest.

Previous studies have generally examined land-cover change using remote sensing and Geographic Information Systems or investigated forest-function conversion through legal and policy analysis. However, these approaches are often applied separately. As a result, the relationship between formal changes in forest designation, actual land-cover dynamics, and the socioeconomic factors driving those changes remains insufficiently understood. An integrated analysis is therefore required to determine whether changes in forest functions are followed by changes in the biophysical condition of the landscape and to evaluate their implications for conservation-area management.

Recent international studies have increasingly employed remote sensing, Google Earth Engine, and machine-learning algorithms to examine land-use and land-cover dynamics. Sun and Ongsomwang (2023) evaluated the optimization of *Random Forest* parameters for land-cover classification using Google Earth Engine, while Pande et al. (2024) demonstrated the effectiveness of an enhanced *Random Forest* model for analysing multi-temporal land-use and land-cover change. Other recent studies have examined land-cover dynamics in protected or managed forests and demonstrated that changes in protection status may increase forest loss, habitat fragmentation, and biodiversity pressures. Thant et al. (2025), for example, reported that land-cover change and deforestation were generally more severe in protected areas affected by legal downgrading, downsizing, or degazettement. Nevertheless, these studies have predominantly focused either on improving spatial-classification techniques or assessing the ecological consequences of changes in protected-area status. Limited attention has been given to integrating legally mandated forest-area

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conversion, empirically observed land-cover dynamics, and institutional explanations derived from relevant government stakeholders, particularly in the context of Indonesian grand forest parks. This study addresses this gap by combining multi-temporal Sentinel-2 classification using *Random Forest*, analysis of forest-area designation documents, and interviews with key forestry officials to examine the conversion and subsequent land-cover dynamics of the Central Sulawesi Grand Forest Park.

Based on these considerations, the principal research problem concerns how land cover has changed following the functional conversion of part of Tahura Central Sulawesi, what factors have driven the conversion, and how the administrative and policy processes were implemented. This study therefore aims to analyze land-cover changes resulting from forest-function conversion, identify the factors contributing to the conversion of part of the Tahura area, and examine the process through which the change in forest function occurred. The study integrates multi-temporal satellite imagery, spatial analysis, policy and document review, field verification, and interviews with relevant institutions as an alternative approach for linking biophysical changes with their policy and socioeconomic contexts.

The findings are expected to provide scientific information for government institutions and other stakeholders involved in the management of Tahura Central Sulawesi. The results may support strategic decision-making, sustainable forest management, spatial monitoring, rehabilitation of degraded land, resolution of tenure conflicts, and the protection of areas with high ecological value. Information on forest conditions, land-cover changes, and changes in forest-area use is essential for sustainable forest management and the formulation of effective forestry policies (FAO, 2020)

2. RESEARCH METHOD

Research design

This study employed a mixed-methods approach by integrating quantitative spatial analysis with qualitative policy analysis. The quantitative component was used to identify changes in forest functions and land-cover conditions, while the qualitative component was used to examine the administrative process, policy considerations, and factors underlying the functional conversion of the Central Sulawesi Grand Forest Park. The integration of both approaches was intended to provide a comprehensive interpretation of the relationship between policy changes and actual landscape dynamics.

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Research location and period

The study was conducted in the Central Sulawesi Grand Forest Park, which is administratively located within Palu City and Sigi Regency, Central Sulawesi Province. Field activities and data collection were carried out from August to October 2025. The area was selected because it is a conservation forest experiencing considerable pressure from land use, settlements, mining activities, and changes in forest-area designation.

Research data

The study used primary and secondary data. Primary data were obtained through interviews with officials and field personnel from the Central Sulawesi Grand Forest Park Management Unit and through field verification. Secondary data consisted of spatial data on the Grand Forest Park and forest-area functions in shapefile format, policy documents, official reports, relevant laws and regulations, and Sentinel-2 satellite imagery.

The spatial data were obtained from Forest Area Consolidation Centre Region XVI Palu, the Central Sulawesi Provincial Forestry Agency, and the Grand Forest Park Management Unit. Satellite imagery for the observation years was accessed through the Google Earth Engine repository. ArcMap version 10.8 and Google Earth Engine were used to process, classify, overlay, and analyze the spatial data. The multi-temporal imagery was used to identify land-cover conditions before and after the change in forest function.

Selection of informants

Informants were selected using purposive sampling based on their knowledge, authority, experience, and direct involvement in the functional conversion and management of the Grand Forest Park. Creswell and Creswell (2018) stated that purposive sampling enables researchers to select participants who can provide the most relevant understanding of the research problem.

The informants comprised the Head of the Central Sulawesi Grand Forest Park Regional Technical Implementation Unit (UPTD), a staff member of the Central Sulawesi Provincial Forestry Service, and a staff member of the Palu Forest Area Consolidation Centre (BPKH) who had direct knowledge of the forest-area conversion process. Semi-structured interviews were conducted in person at the respective informants' offices from August to October 2025, with each interview lasting approximately two hours. The questions focused on proposals for forest-area conversion, technical and legal assessments, stakeholder interests, tenure issues, biophysical considerations, implementation, and post-conversion management. During each interview, the researcher recorded written notes on the key information provided by the informant. The interview

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findings were subsequently organised thematically, compared across institutions, and triangulated with ministerial decrees, maps, technical reports, and field observations. To protect confidentiality, the informants' identities are reported only by their institutional positions because explicit consent to disclose their personal identities was not obtained.

Analysis of forest-function change

The analysis of forest-function change began with the collection and review of primary and secondary data. Primary information was obtained through interviews with officials and personnel directly involved in the functional conversion process. Secondary information included regional spatial plans, ministerial decrees, regional regulations, legislation, forest-area maps, technical reports, and activity reports related to the Grand Forest Park.

The spatial extent of forest-function change was analyzed by overlaying forest-area function maps from different periods. Shapefile data representing conservation forest, Limited Production Forest, and Other Land Use Area were compared to identify the location and extent of functional conversion. The resulting spatial information was presented in maps, tables, and area statistics.

The policy process was examined through document analysis and interviews. The analysis focused on the sequence of proposals, technical assessments, Integrated Team reviews, recommendations, and ministerial decisions. The qualitative findings were then interpreted together with the quantitative spatial results to explain the relationship between policy considerations, functional conversion, and land-cover change.

Land-cover data processing

Sentinel-2 imagery was processed using Google Earth Engine. Sentinel-2 imagery was selected because it provides spatial resolutions of 10–20 m and a high temporal frequency suitable for land-cover mapping and environmental monitoring (Drusch et al., 2012). Google Earth Engine was used because its cloud-computing facilities enable efficient processing of large-scale and multi-temporal geospatial data (Gorelick et al., 2017).

The Grand Forest Park boundary in shapefile format was used to define the Area of Interest. This boundary was applied to clip the imagery and restrict the analysis to the study area. Cloud-contaminated pixels were removed through cloud masking, after which image composites were prepared for each observation year.

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Land-cover classification

The Sentinel-2 predictor stack was classified using the *Random Forest* algorithm (ee.Classifier.smileRandomForest) in Google Earth Engine. The classifier was constructed using 150 decision trees (numberOfTrees). The remaining parameters followed the default settings provided by Google Earth Engine: the square root of the number of input variables for variablesPerSplit, 1 for minLeafPopulation, 0.5 for bagFraction, no specified limit for maxNodes, and 0 for seed. The same classification procedure and model settings were applied to all observation years to maintain temporal comparability.

Reference samples were randomly divided into training and validation datasets using a 70:30 ratio. In 2019, 10,694 samples were used, consisting of 7,557 training samples and 3,137 validation samples. In 2020, 7,267 samples were used, comprising 5,088 training samples and 2,179 validation samples. In 2025, 17,724 samples were used, consisting of 12,382 training samples and 5,342 validation samples. The validation samples were excluded from model training and subsequently used to construct the confusion matrix and calculate *Overall Accuracy*, the Kappa coefficient, and *Producer's Accuracy* for each land-cover class.

The classification procedure consisted of:

1. preparing and filtering Sentinel-2 imagery;
2. applying cloud masking and image compositing;
3. defining the Area of Interest;
4. developing training samples for each land-cover class;
5. separating training and validation samples;
6. applying the Random Forest classifier;
7. calculating the area of each land-cover class; and
8. comparing classification results among observation years.

The classified land-cover categories referred to the national land-cover interpretation guidelines issued by the Indonesian forestry authority and were adjusted to the classes present within the study area.

Land-cover change analysis

Land-cover change was analyzed by comparing classified images from different observation years. Post-classification comparison and spatial overlay techniques were used to identify the conversion of one land-cover class into another. The analysis generated information on

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the location, direction, and extent of changes, including the conversion of forested land into shrubland, open land, agricultural land, settlements, and mining areas.

The area of each land-cover class was calculated in hectares, and the magnitude of change was determined by subtracting the area of a class in the earlier year from that in the later year. The results were presented in transition matrices, statistical tables, and thematic maps to describe the spatial and temporal patterns of land-cover change.

Field verification

Field verification was conducted to confirm whether the land-cover classes interpreted from satellite imagery corresponded with actual conditions. The activity included locating validation points, recording geographic coordinates using a Global Positioning System device, observing land-cover characteristics, documenting field conditions, and collecting information on topography, vegetation, drainage, and land use.

The field data were used as reference information for improving the training samples and evaluating classification results. The field-verification procedure followed the technical principles for satellite-image interpretation and land-cover verification issued by the Ministry of Environment and Forestry (2019).

Accuracy assessment

Classification accuracy was evaluated using a confusion matrix based on independent validation samples. The assessment included Overall Accuracy, Producer's Accuracy, User's Accuracy, and the Kappa coefficient. Overall Accuracy was calculated as the proportion of correctly classified validation samples to the total number of validation samples. Producer's Accuracy represented the probability that a reference sample was correctly classified, whereas User's Accuracy indicated the reliability of a mapped class.

The Kappa coefficient was used to measure agreement between the classified land-cover map and the reference data after accounting for agreement occurring by chance. The interpretation of Kappa values followed the categories presented by Islami et al. (2022): values below 0 indicated very poor agreement; 0.00–0.20, slight agreement; 0.21–0.40, fair agreement; 0.41–0.60, moderate agreement; 0.61–0.80, substantial agreement; and 0.81–1.00, almost perfect agreement.

Data integration and interpretation

The final stage involved integrating the spatial results, accuracy assessment, policy analysis, document review, interview findings, and field observations. Quantitative findings were presented as maps, area statistics, and land-cover transition tables, while qualitative findings were

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presented as descriptive interpretations of the policy process and driving factors. The integrated analysis was used to explain how the change in forest function affected land-cover conditions and to formulate recommendations for the sustainable management of the Central Sulawesi Grand Forest Park

3. RESULT AND DISCUSSION

Changes in the area and function of the Central Sulawesi Grand Forest Park

The Central Sulawesi Grand Forest Park extends across Palu City and Sigi Regency and performs important conservation, hydrological, educational, and recreational functions. It also serves as a catchment area for several rivers, including the Paneki, Watutela, and Kawatuna Rivers. The area was initially designated at 7,128 ha under Minister of Forestry Decree No. 24/Kpts-II/1999. However, Minister of Environment and Forestry Decree No. SK.6624/MENLHK-PKTL/KUH/PLA.2/10/2021 reduced the area retained as Grand Forest Park to 5,149 ha.

Table 1. Changes in the Area and Function of the Central Sulawesi Grand Forest Park

Forest-area designation	Area (ha)	Percentage (%)
Grand Forest Park	5,149	72.24
Limited Production Forest	1,933	27.11
Other Land Use Area	46	0.65
Total	**7,128**	**100.00**

Source: Minister of Environment and Forestry Decree No. SK.6624/MENLHK-PKTL/KUH/PLA.2/10/2021.

As shown in Table 1, approximately 1,979 ha, or 27.76% of the original conservation area, underwent changes in function or designation. Of this area, 1,933 ha was reclassified as Limited Production Forest, while 46 ha was designated as Other Land Use Area. The reduction indicates a substantial adjustment in forest governance to accommodate existing land use, regional development, settlement requirements, and economic activities. Nevertheless, converting a conservation area into a forest category that permits broader utilization may reduce the level of protection afforded to ecologically important landscapes.

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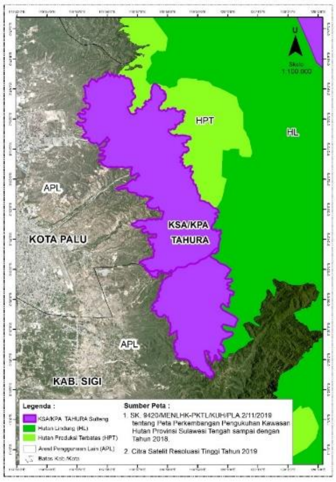

Figure 1: Map of the Central Sulawesi Grand Forest Park Before the Change in Forest-Area Status

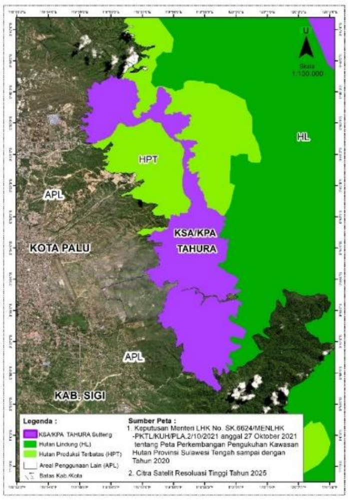

Figure 2: Map of the Central Sulawesi Grand Forest Park After the Change in Forest-Area Status

The reduction of the Central Sulawesi Grand Forest Park from 7,128 ha to 5,149 ha represents more than an administrative boundary adjustment. Based on Minister of Forestry Decree No. 24/Kpts-II/1999, the area was originally designated as a Grand Forest Park covering 7,128 ha. Following the issuance of Minister of Environment and Forestry Decree No. SK.6624/MENLHK-PKTL/KUH/PLA.2/10/2021, approximately 1,933 ha were converted into Limited Production Forest and 46 ha were redesignated as Other Land Use. Consequently, the remaining Grand Forest

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Park accounted for 72.24% of its original area, while approximately 27.76% underwent changes in forest function or allocation.

Conceptually, this reduction can be understood as a form of protected-area downsizing because part of the legally protected area was removed or assigned a different land-use function. Mascia and Pailler (2011) explained that protected-area downgrading, downsizing, and degazettement reflect changes in the legal status, boundaries, or level of protection of conservation areas. Such changes demonstrate that protected areas are not necessarily permanent spatial entities but may be modified in response to social, political, and economic pressures. Therefore, the boundary change in the Central Sulawesi Grand Forest Park should be interpreted as an interaction between conservation objectives and competing interests in land use and development.

The interview and document-review findings indicate that the conversion process was associated with several interrelated factors, including mining and investment interests, tenure claims, existing settlements and community land use, the effects of the 2018 earthquake and liquefaction disaster, and the declining biophysical condition of several parts of the area. This finding is consistent with Mascia et al. (2014), who reported that protected-area boundary and status changes are frequently associated with industrial-scale natural-resource extraction, infrastructure development, local land pressures, land claims, and conservation-planning considerations. Similarly, Symes et al. (2016) found that protected-area changes in tropical and subtropical regions are influenced by interactions among economic accessibility, development pressure, institutional conditions, and competing land-use interests.

Nevertheless, the conversion should not be interpreted solely as a response to development interests. The designation of areas that had already been occupied, cultivated, mined, or substantially altered may also represent an attempt to align their legal status with existing land conditions and management realities. This indicates a discrepancy between the formal conservation status of the area and its actual land use before the conversion. In this context, the conversion process reflects an institutional response to accumulated tenure, land-use, and ecological problems within the former Grand Forest Park boundary.

The findings also show that legal conversion and actual land-cover change are closely related but not identical. A change in legal status does not automatically cause an immediate physical change in land cover. Conversely, forest degradation, settlement development, cultivation, or mining may occur before the formal boundary or forest function is changed. Therefore, the disappearance of mining and the substantial reduction in settlement classes from maps of the

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remaining Grand Forest Park should not be interpreted as evidence that these activities had physically ceased. Instead, these land uses were primarily located in areas excluded from the post-conversion boundary.

This distinction is important because recent international evidence indicates that protected-area downsizing may increase exposure to deforestation, habitat fragmentation, resource extraction, and other anthropogenic pressures when post-conversion areas are not adequately regulated. Thant et al. (2025) found that land-cover change and habitat fragmentation were generally more severe in areas affected by protected-area downgrading, downsizing, or degazettement. Accordingly, changing the status of parts of the Central Sulawesi Grand Forest Park may resolve certain administrative or tenure inconsistencies, but it may also reduce their level of conservation protection and increase the need for monitoring under their new legal status.

Overall, the conversion produced two related management challenges. First, the remaining 5,149-ha Grand Forest Park must be protected from further encroachment, mining, settlement expansion, and agricultural pressure. Second, the converted areas require clear spatial regulation, environmental safeguards, and post-conversion monitoring to prevent uncontrolled land-use change. These findings demonstrate that the effectiveness of the policy should not be evaluated solely from the completion of the legal conversion process, but also from its long-term implications for forest cover, ecological connectivity, tenure resolution, and sustainable land management.

Process of forest-function conversion

The conversion process began during the review of the provincial and municipal spatial plans following the earthquake, tsunami, and liquefaction disaster that affected Palu and its surrounding areas in September 2018. In March 2019, the Palu City Government proposed changes in the function and designation of approximately 2,650 ha of forest land, including an area around Poboya proposed for conversion into Limited Production Forest. The proposal was associated with unlicensed gold-mining activities, prolonged tenure conflicts, and post-disaster economic-development requirements. In September 2019, the Sigi Regency Government also proposed changes that included the conversion of part of Tompu Hamlet, Ngatabaru Village, into Other Land Use Area.

The Provincial Government subsequently submitted and revised the proposal six times between July 2019 and March 2020. These revisions reflected continuing adjustments to spatial data, field conditions, local development priorities, and the results of interagency coordination. The

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repeated submission process indicates that the conversion was not implemented through a single administrative decision but developed through a series of technical and institutional negotiations.

Table 2. Main Stages of the Forest-Function Conversion Process

Stage	Main activity	Period
Initiation	Post-disaster spatial-plan review and proposals from Palu City and Sigi Regency	2018–2019
Provincial submission	Compilation, revision, and finalization of the provincial proposal	2019–2020
Integrated Team assessment	Spatial analysis, plenary review, field verification, and consistency assessment	2019–2020
Recommendation	Formulation of technical recommendations for changes in forest function and designation	2020
Ministerial designation	Formal designation through ministerial decrees	2020–2021

The Minister of Environment and Forestry established an Integrated Team through Decree No. SK.885/MENLHK/SETJEN/PLA.0/10/2019. The team assessed the proposals by considering biophysical, environmental, spatial, social, economic, and legal aspects. Its activities included GIS analysis, plenary discussions, field verification, stakeholder consultations, and the preparation of recommendations. The results were subsequently formalized through Decree No. SK.452/MENLHK/SETJEN/PLA.0/11/2020 and finally incorporated into Decree No. SK.6624/MENLHK-PKTL/KUH/PLA.2/10/2021.

The process complied procedurally with the legal mechanisms governing changes in forest function and designation. However, procedural compliance does not necessarily guarantee that the resulting policy will maintain the ecological effectiveness of the former conservation area. Forest-policy changes commonly emerge from interactions among conservation, spatial planning,

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development, economic investment, and community interests rather than from ecological considerations alone (Maryudi et al., 2019; Nurprabowo et al., 2021).

The interviews with representatives of the Central Sulawesi Grand Forest Park Management Unit, the Central Sulawesi Provincial Forestry Service, and the Palu Forest Area Consolidation Centre revealed that the change in forest function was driven by multiple and interrelated considerations. The principal themes identified from the interviews included discrepancies between the legal designation and actual land use, tenure claims, settlements and community activities, mining and investment interests, the impacts of the 2018 earthquake and liquefaction disaster, and the declining biophysical condition of several parts of the area. The consistency of these themes across the three institutions indicates that the conversion was not caused by a single factor but resulted from the accumulation of social, economic, ecological, and administrative pressures.

A central issue identified by the informants was the discrepancy between the formal conservation status of the Grand Forest Park and the actual condition of land use within its former boundary. Before the conversion, several locations had already been occupied, cultivated, settled, or used for mining-related activities. Consequently, the entire area designated under Minister of Forestry Decree No. 24/Kpts-II/1999 no longer exhibited uniform conservation characteristics. This finding is consistent with previous studies showing that forest governance problems frequently arise when statutory forest boundaries overlap with long-established community occupation, customary claims, and other land uses (Maryudi et al., 2019). Such discrepancies can generate prolonged tenure uncertainty and weaken the effectiveness of conservation-area management.

The interview findings also help explain the spatial results. Mining and settlement classes were identified within the original 2019 Grand Forest Park boundary but were substantially reduced or no longer recorded in the post-conversion maps. This pattern should not be interpreted as evidence that these activities had physically disappeared. Instead, the areas in which they were concentrated—particularly Poboya and parts of Tompu Hamlet—were largely excluded from the remaining 5,149-ha Grand Forest Park. The agreement between the interview information, ministerial decrees, and spatial analysis confirms that the apparent change in these land-cover classes was primarily associated with boundary modification.

Tenure issues were another important consideration reported by the informants. Community occupation and land use had developed in parts of the area before the formal

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conversion was completed, creating uncertainty regarding access, control, and management responsibility. Similar conditions have been reported in Indonesian forest governance studies, in which overlapping claims and limited recognition of local land-use histories contributed to conflict and reduced policy effectiveness. Accordingly, changing the forest function may clarify the legal status of certain areas, but it does not automatically resolve existing tenure disputes. Further participatory boundary clarification, conflict mediation, and recognition of legitimate community interests remain necessary.

The informants further indicated that the 2018 earthquake and liquefaction disaster influenced the assessment of the area's physical and social conditions. The disaster altered parts of the landscape, affected settlements and infrastructure, and increased pressure for reconstruction and spatial reorganisation. However, the disaster should not be treated as the sole cause of the conversion. Rather, it intensified pre-existing problems involving tenure, settlement, accessibility, land degradation, and competing development interests. This interpretation demonstrates that environmental disasters can interact with existing institutional and land-use pressures, thereby accelerating demands for policy and boundary adjustments.

The interview findings are also consistent with the broader literature on protected-area downsizing. Mascia and Pailler (2011), Mascia et al. (2014), and Symes et al. (2016) demonstrated that changes in protected-area boundaries commonly occur through interactions among resource-extraction interests, infrastructure and economic development, local land claims, and conservation-planning considerations. The Central Sulawesi case shows a comparable pattern, although it also presents a context-specific factor in the form of the 2018 disaster. Thus, the conversion represents both an institutional response to existing land-use realities and a policy decision that may create new environmental risks if the converted areas are not adequately managed.

Triangulation of the interview findings with ministerial decrees, land-cover maps, technical documents, and field observations strengthened the interpretation of the conversion process. The interviews explained the institutional and social factors underlying the spatial patterns, while the spatial analysis provided measurable evidence of land-cover conditions before and after the conversion. Nevertheless, because the qualitative findings were based on three institutional informants, they primarily represent government and management perspectives. Future studies should therefore include affected communities, customary groups, mining actors, environmental organisations, and other stakeholders to obtain a more comprehensive understanding of the process.

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Overall, the interviews demonstrate that the conversion cannot be evaluated solely as a completed administrative procedure. Its effectiveness will depend on whether the policy can improve management of the remaining Grand Forest Park, prevent further encroachment and degradation, resolve tenure-related problems, and ensure environmental control in the converted areas. Continued monitoring and coordination among forestry institutions, local government, communities, and other stakeholders are therefore required to prevent the boundary change from generating additional land-use conflicts or ecological pressures.

Accuracy of land-cover classification

The reliability of the land-cover maps was assessed using Overall Accuracy and the Kappa coefficient. The Random Forest classifications produced high Overall Accuracy values for all observation years.

Table 3. Accuracy Assessment of Land-Cover Classification

Year	Number of classes	Overall Accuracy (%)	Kappa coefficient	Interpretation
2019	9	92.99	0.88	Almost perfect agreement
2020	8	89.77	0.81	Almost perfect agreement
2025	8	95.30	0.86	Almost perfect agreement

The Overall Accuracy values ranged from 89.77% to 95.30%, while the Kappa coefficients ranged from 0.81 to 0.88. These results indicate that the classifications were sufficiently reliable for detecting major land-cover patterns and changes. Primary dryland forest and grassland generally had the highest Producer's Accuracy. In contrast, water bodies, settlements, and some heterogeneous vegetation classes had lower values because of limited reference samples, seasonal river conditions, small object sizes, and spectral similarity among land-cover classes.

The Producer's Accuracy of settlements was 0% in 2020 and 2025. This result does not necessarily indicate the absence of settlements, but rather that the very small mapped settlement area was inadequately represented in the validation sample. Consequently, changes involving small settlement and water-body classes should be interpreted cautiously. The Random Forest

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classifications demonstrated strong overall performance across the three observation years. The 2019 classification achieved an Overall Accuracy of 92.99% and a Kappa coefficient of 0.8855, while the 2020 classification obtained an Overall Accuracy of 89.77% and a Kappa coefficient of 0.81. The highest performance was recorded in 2025, with an Overall Accuracy of 95.30% and a Kappa coefficient of 0.86. Based on the criteria proposed by Landis and Koch (1977), the Kappa values for all three years indicate almost perfect agreement between the classified results and the reference data. These results demonstrate that Random Forest was generally reliable for identifying the principal land-cover classes in the study area. The findings are consistent with Sun and Ongsomwang (2023) and Pande et al. (2024), who reported that Random Forest performs effectively in multi-temporal land-cover classification using Sentinel-2 imagery and the Google Earth Engine platform.

Despite the high overall accuracy, classification performance varied considerably among land-cover classes. Primary forest consistently achieved the highest Producer’s Accuracy, reaching 98.73% in 2019, 97.39% in 2020, and 99.93% in 2025. Grassland also showed consistently high accuracy, ranging from 93.14% to 95.67%. The high accuracy of these classes indicates that their spectral and spatial characteristics were relatively distinctive in the Sentinel-2 imagery. A similar pattern has been reported in previous studies, which found that classes with extensive and relatively homogeneous cover are generally more accurately classified by Random Forest than spatially fragmented or spectrally heterogeneous classes.

In contrast, water bodies consistently recorded relatively low Producer’s Accuracy, with values of 48.28% in 2019, 46.67% in 2020, and 40.00% in 2025. This result may be associated with the presence of narrow or seasonal river channels, mixed pixels along riverbanks, and spectral similarities between shallow or dry watercourses and open land or sparsely vegetated areas. Secondary forest accuracy also decreased from 82.59% in 2019 to 68.21% in 2020 and 46.35% in 2025. This decline may reflect increasing spectral overlap between secondary forest, mixed dryland agriculture, and shrubland because these classes contain heterogeneous vegetation structures and different stages of vegetation succession.

The settlement class obtained a Producer’s Accuracy of 71.88% in 2019 but 0% in both 2020 and 2025. This result does not necessarily indicate the complete absence of settlements; rather, it suggests that the reference samples for this class were insufficient or were not successfully represented by the classifier. Consequently, estimates of changes involving settlements should be interpreted cautiously. More balanced reference samples and additional

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predictor variables, such as spectral indices or texture measures, may improve the discrimination of small and heterogeneous classes in future classifications.

Overall, the high Overall Accuracy and Kappa values support the use of the classification results for analysing broad land-cover patterns and changes. Nevertheless, the variation in class-level accuracy indicates that changes involving water bodies, settlements, secondary forest, and mixed dryland agriculture should be interpreted more cautiously, particularly when the estimated differences are relatively small. Thus, Overall Accuracy alone should not be used as the sole indicator of classification reliability; class-specific accuracy must also be considered when interpreting land-cover change.

Land-cover conditions before and after the change in forest function

In 2019, before the revised forest-area designation, the analysis covered the original 7,128-ha Grand Forest Park. Forest cover dominated the area, consisting of 2,965.72 ha of primary dryland forest and 2,702.56 ha of secondary dryland forest. Together, these classes accounted for 5,668.28 ha or 79.52% of the area.

Table 4. Land Cover of the Central Sulawesi Grand Forest Park in 2019

Land-cover class	Area (ha)	Percentage (%)
Primary dryland forest	2,965.72	41.61
Secondary dryland forest	2,702.56	37.91
Mixed dryland agriculture	319.37	4.48
Settlement	28.21	0.40
Mining area	33.67	0.47
Open land	61.70	0.87
Grassland	633.81	8.89
Shrubland	365.43	5.13
Water body	17.55	0.25
Total	**7,128.00**	**100.00**

The 2019 classification identified mining areas and settlements within the original Grand Forest Park boundary. Most mining areas were concentrated around Poboya, while settlements and associated infrastructure were found around Tompu Hamlet. After the forest-function conversion, these locations were largely excluded from the remaining Grand Forest Park. Therefore, the disappearance of mining and the substantial reduction in settlement classes in the

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subsequent analysis primarily resulted from boundary changes rather than the physical disappearance of these land uses.

The analysis for 2020 and 2025 was limited to the remaining 5,149-ha Grand Forest Park. In 2020, primary and secondary dryland forests covered 81.42% of the area. By 2025, their combined share remained high at 80.52%.

Table 5. Land-Cover Composition of the Remaining Grand Forest Park, 2020–2025

Land-cover class	2020 (ha)	2020 (%)	2025 (ha)	2025 (%)	Change (ha)
Primary dryland forest	2,846.14	55.28	3,105.38	60.31	+259.24
Secondary dryland forest	1,346.09	26.14	1,040.47	20.21	−305.62
Mixed dryland agriculture	248.80	4.83	139.36	2.71	−109.44
Settlement	0.04	0.00	0.04	0.00	0.00
Open land	35.91	0.70	20.72	0.40	−15.19
Grassland	423.21	8.22	288.71	5.61	−134.50
Shrubland	242.96	4.72	553.75	10.75	+310.79
Water body	5.85	0.11	0.57	0.01	−5.28
Total	**5,149.00**	**100.00**	**5,149.00**	**100.00**	**0.00**

A direct numerical comparison between the 2019 and post-conversion results should be made cautiously because the spatial extent of the analysis changed. The 2019 classification covered the original 7,128-ha Grand Forest Park, whereas the 2020 and 2025 classifications covered only the remaining 5,149 ha. Therefore, the disappearance of mining areas and the substantial reduction in settlements after 2019 primarily reflect the exclusion of Poboya and parts of Tompu Hamlet from the Grand Forest Park boundary rather than the complete physical disappearance of these land uses. This finding demonstrates that changes in mapped land-cover composition may result from both actual landscape dynamics and changes in the legal boundary of the analysed area. Similar concerns have been raised in protected-area studies, where administrative boundary changes may alter reported land-cover statistics without necessarily representing equivalent ecological recovery.

Within the consistently delineated 5,149-ha area, the combined proportion of primary and secondary dryland forest remained relatively stable, decreasing slightly from 81.42% in 2020 to 80.52% in 2025. However, substantial changes occurred between the two forest classes. Primary dryland forest increased by 259.24 ha, from 2,846.14 ha to 3,105.38 ha, whereas secondary dryland forest decreased by 305.62 ha, from 1,346.09 ha to 1,040.47 ha. This pattern may indicate canopy

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development, vegetation maturation, or differences in spectral responses between the observation years. It is consistent with Chazdon's (2014) explanation that secondary vegetation may gradually develop greater canopy cover and structural complexity through natural succession when disturbance is reduced. Nevertheless, the increase in the mapped primary-forest class should not automatically be interpreted as the ecological recovery of secondary forest into primary forest. As emphasised by Congalton and Green (2019), remotely sensed classifications represent spectral categories, and ecological transitions require confirmation through long-term vegetation inventories, stand-age information, and field observations.

Shrubland experienced the largest increase, expanding by 310.79 ha, from 242.96 ha in 2020 to 553.75 ha in 2025. During the same period, grassland decreased by 134.50 ha, mixed dryland agriculture by 109.44 ha, and open land by 15.19 ha. These simultaneous changes suggest that portions of previously open, grass-covered, or cultivated land may have entered an early stage of vegetation succession. This interpretation is consistent with Chokkalingam et al. (2001) and Chazdon (2014), who described shrub-dominated vegetation as a transitional stage in the recovery of disturbed tropical landscapes. Reduced cultivation or disturbance may permit grasses and pioneer shrubs to colonise exposed land before the development of more structurally complex secondary forest.

However, the expansion of shrubland should not be considered equivalent to complete forest recovery. Compared with mature forest, shrubland generally has lower canopy complexity, biomass storage, habitat quality, and capacity to provide hydrological services. Dumitraşcu et al. (2020) similarly showed that changes in forest-related land-cover classes within a protected natural park reflected not only recovery processes but also continuing anthropogenic pressures and landscape fragmentation. Accordingly, the observed increase in shrubland in the Central Sulawesi Grand Forest Park indicates a transitional landscape condition that requires continued protection and monitoring before ecological recovery can be confirmed.

The decline in mixed dryland agriculture may indicate reduced cultivation within the remaining Grand Forest Park, abandonment of agricultural plots, or their gradual replacement by shrub vegetation. Nevertheless, this interpretation must be considered alongside the interview findings, which revealed continuing tenure and land-use pressures in several locations. Thus, a decrease in the mapped agricultural class does not necessarily indicate that community–forest interactions or tenure conflicts have been fully resolved. Instead, it may reflect changes in

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cultivation intensity, vegetation cover, or the spectral characteristics of temporarily abandoned plots.

Overall, the results indicate that the remaining Grand Forest Park continued to be dominated by forest cover between 2020 and 2025, but its internal land-cover composition remained dynamic. The increase in primary-forest and shrubland classes may suggest vegetation development in some locations, while the decrease in secondary forest and the lower Producer's Accuracy of this class in 2025 require cautious interpretation. These findings imply that land-cover improvement should not be assessed solely from increases in vegetated area. Field verification and periodic monitoring are required to determine whether the observed changes represent genuine ecological recovery, temporary vegetation succession, or classification uncertainty.

Influence of forest-function conversion on land-use patterns

The conversion of part of the Grand Forest Park into Limited Production Forest had its most visible consequences around Poboya. The new designation provided a legal framework through which forest land could be used for mining under a Forest Area Use Approval. PT Citra Palu Minerals subsequently obtained approval to use approximately 327.13 ha of Limited Production Forest for gold-production activities and associated facilities.

The spatial findings suggest that changes in legal designation were associated with a redistribution of land-use pressure. Mining was no longer detected inside the remaining Grand Forest Park boundary in 2020 and 2025 because the principal mining area had been incorporated into Limited Production Forest. This does not indicate that mining pressure had ceased; rather, it had shifted outside the revised conservation boundary. Changes in forest status can therefore influence land-cover statistics by modifying both the legal use of land and the spatial unit used in the analysis.

A similar situation occurred in Tompu Hamlet. The conversion of 46 ha into Other Land Use Area removed established settlements, roads, and public facilities from the conservation boundary. The almost complete disappearance of the settlement class in the 2020 and 2025 maps consequently reflects boundary adjustment rather than physical settlement removal. This distinction is important because comparisons between 2019 and later years do not use identical spatial extents.

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Factors driving forest-function conversion

The conversion was driven by several interrelated factors rather than a single cause. The principal factors identified from policy documents, interviews, and field observations are summarized in Table 6.

Table 6. Factors Driving Forest-Function Conversion

Driving factor	Main evidence and interpretation
Economic and mining interests	Mineral potential in Poboya, existing mining activities, investment objectives, employment expectations, and the need for legal certainty
Social and tenure conflicts	Long-established community occupation, overlapping land claims, unlicensed mining, and disputes among communities, government, and permit holders
Post-disaster spatial requirements	Reconstruction, relocation, infrastructure development, and spatial-plan revision following the 2018 disaster
Biophysical degradation	Vegetation loss, soil disturbance, land-cover degradation, and reduced conservation effectiveness in heavily disturbed areas
Spatial-policy adjustment	Harmonization of forest designation with provincial and municipal spatial plans

Economic considerations were particularly influential in Poboya because of the area's gold resources and long history of mining. Reclassification into Limited Production Forest enabled mining to be regulated through formal forest-use approval. Although such arrangements may contribute to investment, employment, and local revenue, they also create risks of vegetation loss, soil disturbance, and pollution. Hartati et al. (2023) emphasized that mining within forest areas must operate through legal mechanisms and remain consistent with sustainable-development principles.

Social and tenure considerations were also important. Unlicensed mining in Poboya involved multiple actors with competing claims over mineral resources. Such conditions commonly generate governance conflicts because the interests of communities, governments, and formal permit holders overlap (Spiegel et al., 2018). In Tompu Hamlet, settlements reportedly existed before the formal designation of the Grand Forest Park. The presence of schools, places of worship, houses, and old graves indicates long-term occupation. Chamdani (2021) argued that tenure problems involving communities that predate formal forest designation require solutions that consider historical occupation, social conditions, and legal certainty.

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The 2018 earthquake, tsunami, and liquefaction disaster also accelerated the review of regional spatial plans. The disaster damaged settlements and infrastructure and created new requirements for relocation, reconstruction, and regional economic recovery. Consequently, post-disaster planning became an important context within which changes in forest designation were considered.

Biophysical degradation was used as an additional technical consideration. Long-term mining and land-use pressure had altered vegetation, soils, and land-cover conditions in parts of Poboya. However, degraded ecological conditions should not automatically justify reduced protection because changing the legal status of degraded conservation land may create incentives for further exploitation. Reclassification should therefore be accompanied by rehabilitation obligations and effective environmental monitoring.

Legal conformity and policy conflict

The change in forest function and designation followed the procedures established under Law No. 41 of 1999, Government Regulation No. 104 of 2015, Government Regulation No. 23 of 2021, and Minister of Environment and Forestry Regulation No. 7 of 2021. The process included proposals from local governments, spatial and technical assessment, review by an Integrated Team, recommendation, and ministerial approval. From a formal legal perspective, the procedure was therefore consistent with the applicable forestry framework.

Substantively, however, the policy created tension between spatial-development objectives and conservation principles. Spatial-planning policy seeks to allocate land for development, investment, infrastructure, settlement, and public welfare. Conservation policy, in contrast, seeks to preserve ecological functions, biodiversity, and environmental services. The reclassification of 27.76% of the original Grand Forest Park illustrates how these policy objectives may compete.

Table 7. Contrasting Orientations of Spatial-Planning and Conservation Policies

Aspect	**Spatial-planning policy**	**Conservation policy**
Main objective	Regional development and efficient spatial utilization	Protection of ecosystems and biodiversity
Dominant orientation	Economic growth, infrastructure, and community needs	Long-term ecological sustainability
Indicator of success	Increased development and economic activity	Maintenance of forest cover and ecosystem functions
Potential implication	Greater allocation of land for utilization	Restriction of activities that may alter forest functions

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Although the conversion may be viewed as an adaptive response to development and tenure problems, reducing the size of a conservation area may increase habitat fragmentation and weaken ecosystem protection (Primack, 2020). The policy should therefore be evaluated not only according to its legal validity but also according to its ecological outcomes after implementation.

Ecological implications and management priorities

The loss of approximately 1,979 ha from the conservation designation may affect watershed protection, biodiversity, erosion control, and local hydrological regulation. Tahura Central Sulawesi forms part of an important catchment system for Palu and its surroundings. Reducing protected forest area may decrease infiltration capacity and increase the risks of erosion, flooding, and seasonal water shortages. Ellison et al. (2017) explained that forest loss can disrupt hydrological cycles and weaken landscape-scale water regulation.

Mining activities also create potential risks of soil and water contamination, particularly where mercury is used in small-scale gold processing. Mercury may accumulate in soils, sediments, water bodies, and food chains, creating ecological and human-health risks (UNEP, 2019). Strong monitoring of mining operations, wastewater management, hazardous-material use, rehabilitation, and post-mining restoration is therefore essential.

The designation of Tompu Hamlet as Other Land Use Area may improve legal certainty and access to public infrastructure. However, improved road access may also facilitate encroachment, illegal logging, mining, and settlement expansion into adjacent forest areas. Roads in forest landscapes are frequently associated with increased habitat fragmentation and human disturbance (Forman & Alexander, 1998; Benítez-López et al., 2010; Barber et al., 2014; Laurance et al., 2014).

Management implications

The findings have several important implications for the management of the Central Sulawesi Grand Forest Park. First, the remaining primary dryland forest, which covered 3,105.38 ha or 60.31% of the Grand Forest Park in 2025, should be treated as the principal conservation priority. Its dominance indicates that the remaining area retains substantial ecological value in terms of biodiversity conservation, carbon storage, habitat provision, and watershed protection. Management efforts should therefore focus on preventing further encroachment, mining, settlement expansion, agricultural conversion, and infrastructure development within intact forest areas. Regular patrols, boundary demarcation, and community-based monitoring are required, particularly in locations adjacent to settlements and areas affected by previous land-use pressure.

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Second, rehabilitation should be prioritised in areas classified as shrubland, grassland, open land, and degraded secondary forest. The substantial expansion of shrubland from 242.96 ha in 2020 to 553.75 ha in 2025 indicates that several locations remain in a transitional stage of vegetation recovery. Although shrub development may represent an early stage of natural succession, it should not automatically be considered equivalent to forest restoration. Rehabilitation strategies should therefore be adapted to site conditions through assisted natural regeneration, enrichment planting with native species, erosion control, and the restoration of ecological connectivity between fragmented forest patches. Field verification is necessary to distinguish areas undergoing natural recovery from those still experiencing recurrent disturbance.

Third, post-conversion monitoring should cover both the remaining 5,149-ha Grand Forest Park and the areas whose functions or allocations were changed. Monitoring should not be limited to administrative compliance but should assess changes in forest cover, habitat fragmentation, mining and cultivation activities, settlement expansion, and environmental quality. Comparable satellite imagery, consistent classification boundaries, field observations, and periodic accuracy assessments should be used to evaluate long-term changes. Particular attention should be given to areas converted into Limited Production Forest and Other Land Use because their reduced conservation status may increase exposure to extraction and uncontrolled land-use change. The effectiveness of the conversion policy should consequently be evaluated from its environmental outcomes rather than solely from the completion of the legal process.

Fourth, changing the legal status or boundary of the area does not automatically resolve tenure conflicts. Participatory boundary clarification is therefore required to identify legitimate claims, customary interests, existing community land use, and areas affected by overlapping permits or administrative designations. Conflict resolution should involve the Grand Forest Park Management Unit, the Provincial Forestry Service, the Forest Area Consolidation Centre, local governments, customary institutions, and affected communities. Mediation, transparent spatial information, and mutually agreed management arrangements are essential to prevent unresolved claims from generating further encroachment or conflict.

Overall, the management of the Central Sulawesi Grand Forest Park requires an integrated approach that combines strict protection of intact primary forest, targeted rehabilitation of degraded land, continuous monitoring of both retained and converted areas, and participatory tenure-conflict resolution. These measures are necessary to ensure that the forest-function

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conversion improves legal and administrative clarity without weakening ecological protection or transferring environmental and social pressures to areas outside the remaining Grand Forest Park.

4. CONCLUSION

This study demonstrates that the change in forest function reduced the Central Sulawesi Grand Forest Park from 7,128 ha to 5,149 ha, with 1,933 ha converted into Limited Production Forest and 46 ha redesignated as Other Land Use. In 2025, the remaining Grand Forest Park was dominated by primary dryland forest, covering 3,105.38 ha or 60.31% of the area. Between 2020 and 2025, primary dryland forest and shrubland increased, while secondary dryland forest, grassland, mixed dryland agriculture, and open land decreased. However, these changes should not automatically be interpreted as complete ecological recovery because they may also reflect vegetation succession, differences in spectral response, and classification uncertainty.

The scientific contribution of this study lies in integrating multi-temporal Random Forest land-cover classification with document analysis, field observations, and institutional interviews to distinguish physical land-cover dynamics from changes caused by legal boundary modification. This integrated approach demonstrates that the apparent disappearance or reduction of mining and settlement classes after 2019 primarily resulted from the exclusion of Poboya and parts of Tompu Hamlet from the Grand Forest Park boundary, rather than the complete cessation of these activities. The study therefore provides evidence that legal changes in protected-area boundaries and actual ecological changes are closely related but should be analysed as distinct processes.

From a policy perspective, the remaining primary forest should become the main conservation priority, while shrubland, grassland, open land, and degraded secondary forest should be targeted for rehabilitation and field verification. Post-conversion monitoring should cover both the remaining Grand Forest Park and the areas converted into Limited Production Forest and Other Land Use to prevent further forest degradation, uncontrolled mining, settlement expansion, and agricultural encroachment. Participatory boundary clarification and tenure-conflict resolution involving government institutions, customary groups, and affected communities are also required because changes in legal status do not automatically resolve overlapping land claims and existing land-use conflicts.

This study has several limitations. The 2019 land-cover analysis used the original 7,128-ha boundary, whereas the 2020 and 2025 analyses used the remaining 5,149-ha boundary; consequently, direct comparisons between 2019 and the subsequent years must be interpreted

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cautiously. Some land-cover classes—particularly settlements, water bodies, and secondary forest—also had relatively low Producer's Accuracy, which increases uncertainty in class-specific change estimates. Furthermore, the qualitative analysis involved only three institutional informants and therefore mainly represents government and management perspectives. Future research should apply a consistent spatial boundary across all observation years, incorporate longer-term imagery and ecological field measurements, improve reference sampling for low-accuracy classes, and involve affected communities, customary groups, mining actors, and other stakeholders.

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