



Full Length Research Article

Land Cover Change and Ecosystem Services Trade-Off in the Tiworo Watershed: Implications for Forest Conservation and Watershed Management

Safril Kasim^{1,*} , Hasddin² , La Fariki³ , Abhishek Agarwal⁴ 

¹ Department of Environmental Sciences, Faculty of Forestry and Environmental Sciences, Halu Oleo University, Kendari, Indonesia

² Department of Regional and Urban Planning, Lakidende University, Unaaha, Indonesia

³ Southeast Sulawesi Province Regional Research and Innovation Agency, Kendari, Indonesia

⁴ Department of Energy Technology, Tallinn University of Technology, Tallinn, Estonia

* Corresponding author. E-mail address: safrikasim1970@gmail.com

ARTICLE HISTORY:

Received: 3 October 2025

Peer review completed: 4 March 2026

Received in revised form: 15 April 2026

Accepted: 1 May 2026

KEYWORDS:

Ecosystem services
Forest management
Land cover change
Tapio decoupling
Tiworo Watershed

ABSTRACT

This study evaluates the spatio-temporal dynamics of land-cover change and their implications for the sustainability of ecosystem services in the Tiworo Watershed, Southeast Sulawesi, Indonesia, using an integrated ecological–economic framework. The analysis combined land cover datasets from 2014, 2019, and 2024 with sectoral gross regional domestic product (GRDP) data for agriculture, forestry, and fisheries, and applied the Tapio decoupling model to assess the relationship between economic growth and ecological pressure. Results revealed substantial expansion of built-up areas, plantations, and aquaculture ponds, primarily at the expense of mangrove forests and wetlands. Mangrove cover declined from 431.61 ha in 2014 to 306.77 ha in 2024, indicating increasing pressure on coastal ecosystems. Despite these changes, secondary dryland agriculture and forest areas remained relatively stable, suggesting partial resilience of the watershed landscape. Economically, the agriculture, forestry, and fisheries sector consistently contributed 38–41% of regional GRDP, confirming its strategic importance to local livelihoods and regional development. Decoupling analysis demonstrated absolute decoupling during 2014–2019 and 2014–2024, while relative decoupling occurred during 2019–2024, indicating that economic growth increasingly outpaced ecological degradation. However, localized ecosystem degradation, particularly in mangrove areas, remains a critical concern. These findings highlight that the Tiworo Watershed is transitioning toward more resource-efficient development. However, long-term sustainability depends on adaptive watershed governance, stricter protection of vulnerable ecosystems, improved land-use planning, and strengthened community-based forest management. The study provides empirical evidence supporting the application of decoupling analysis at the tropical micro-watershed scale and contributes to the development of integrated forest and watershed management strategies in data-limited regions.

© 2026 The Authors. Published by the Department of Forestry, Faculty of Agriculture, University of Lampung. This is an open access article under the CC BY-NC license: <https://creativecommons.org/licenses/by-nc/4.0/>.

1. Introduction

Land cover change is among the most significant environmental issues in tropical areas, especially in watersheds (*Daerah Aliran Sungai/DAS*), which not only serve as ecosystem buffers but also strategic locations for nature-based economic activities. Watersheds, therefore, are not

only the means of maintaining the hydrological balance, soil fertility, and biodiversity, but also the agriculture, forestry, and fisheries sectors that form the backbone of the local economies. Nevertheless, the conversion of land through deforestation, agricultural expansion, mangrove forest degradation, and the intensification of land use have radically altered the ecosystem's structure and functions. This has put the availability of ecosystem services under significant pressure, both in quantity and quality. This is evidenced by recent studies on mangrove dynamics, land-use change, and the impact of deforestation on ecosystem function (Darmawan and Santoso 2024; Faria et al. 2023; Iskandar et al. 2024; Latifah 2025; Villareal et al. 2025).

Various studies have shown that the degradation of forest cover and watershed ecosystems has a direct impact on both the biophysical and socio-economic aspects of communities. The loss of forests and mangroves, reduced soil fertility, decreased clean water availability, and decreased productivity of capture fisheries and aquaculture have implications for household income, food security, and the well-being of coastal and rural communities (Costanza et al. 2017; Costanza 2024; Dewi et al. 2024; Nugroho et al. 2021). Such events have been documented in different tropical regions, e.g., Tanzania (Msofe et al. 2020) and Ethiopia (Aneseyee et al. 2022; Assefa et al. 2021), where the transformation of the land has resulted in a decline in ecosystem services and increased the socio-economic vulnerability of the local communities (Bernales et al. 2025; Pulido et al. 2025; Samrin et al. 2024).

Many studies have been made on how changes in land cover affect ecosystem services and have mainly put forward issues of forest degradation, biodiversity loss, and their effects on ecosystem services (Admasu et al. 2023; Msofe et al. 2020; Mulyana et al. 2024; Rahmadwiati et al. 2021). Nevertheless, comprehensive studies in Indonesia remain scarce. The majority of research focuses only on the biophysical aspects of land cover change or on the monetary valuation of ecosystem services by sector (Jasman et al. 2023; Kasim et al. 2024; Nahib et al. 2024; Sari et al. 2021). However, integrating these two sides (environment and economics) is vital for understanding the link between natural resource sustainability and local development (Sampurno 2023). Such a comprehensive model can disclose the trade-offs and possible separation of economic growth from ecological sustainability (García-Rubio et al. 2024; Velasco-Muñoz et al. 2022), which is quite significant for the Indonesian archipelagic and coastal areas where agriculture, forestry, and fisheries are the leading sectors of gross regional domestic product (GRDP) (Utomo et al. 2025).

Food, timber, clean water, and fisheries are some examples of ecosystem provisioning services that play a basic role within an ecological-economic framework. These services meet basic community needs and serve as the foundation for primary sector productivity (Azadi et al. 2021; Dewi et al. 2024; García-Rubio et al. 2024). In island and rural areas, including West Muna Regency, these ecosystem services are crucial for food security and local economic stability. Therefore, assessing and monitoring the sustainability of ecosystem services is key to designing sustainable development that balances natural resource conservation with economic growth.

Sectoral GRDP from an economic perspective could be considered a numerical indicator of nature services, mainly for the agriculture, forestry, and fisheries sectors. The value added recorded in GRDP not only reflects the ecosystem's real contribution to the formal economy but also serves as a signal of the potential for integration with ecosystem services accounting frameworks (de Groot et al. 2020; Masiero et al. 2019). The GRDP analysis during the period 2014–2024 is essential, among other reasons, because it covers the post-division period of the West Muna

Regency, a period marked by intensified land-cover change, commodity price fluctuations, and development dynamics.

Empirically, significant changes in land cover in the Tiworo Watershed have been recorded. [Taufik et al. \(2021\)](#) reported deforestation of approximately 1,107.62 ha between 2010 and 2020. In some cases, these land cover changes reduced natural vegetation cover, decreased hydrological capacity, and increased waterlogging ([Tarmizi and Rizwan 2024](#); [Ulqodry et al. 2025](#); [Villareal et al. 2025](#)). Furthermore, [Tunda et al. \(2025\)](#) emphasized the importance of studying sustainable management of the Tiworo Watershed. Therefore, identifying several sensitive attributes that influence watershed pressure is important for strategic planning for community adaptation, land-use regulation, and human-resource capacity building ([Imran et al. 2021](#)). Such environmental pressures, particularly land-use changes, are expected to affect the local economy. [Hasddin \(2019\)](#) reported that natural resources in the Tiworo River Basin have a total economic value of IDR 470.9 billion. Interestingly, approximately 55% of this value comes from the agriculture, inland fisheries, forestry, and ecotourism subsectors. This presents a paradox: degraded ecosystems are the foundation of the local economy, yet remain highly vulnerable to conflicts over natural resource use and ecological sustainability.

One of the major ways to theoretically quantify the interaction of economic growth and land-cover change on a sectoral level is, without a doubt, the trade-off and decoupling framework by Tapio ([Shang and Luo 2021](#); [Wang et al. 2023](#)). This model is instrumental for understanding whether economic growth is the main driver of ecosystem degradation (coupling), if economic growth is outpacing ecological pressures (relative decoupling), or if economic growth is completely detached from ecological degradation (absolute decoupling) ([Jing et al. 2024](#)). Therefore, sectoral GRDP-based analysis is not just a metric of economic performance but also an indicator of the ecosystem's potential to provide production-support services. This study aims to assess land cover changes in the Tiworo Watershed and examine their relationship with sectoral GRDP in agriculture, forestry, and fisheries using the Tapio decoupling framework. This approach provides a clearer understanding of trade-offs between economic growth and ecosystem dynamics, which is essential for ecologically sustainable watershed management.

This study offers a novel contribution by integrating spatio-temporal land cover change analysis with sectoral GRDP dynamics within a Tapio decoupling framework at the watershed scale in a tropical, data-limited region of Eastern Indonesia. Previous studies generally assess decoupling at national or regional scales or focus separately on biophysical or economic dimensions. In contrast, this study explicitly links ecological capacity (land cover) with sectoral economic performance (GRDP) to reveal localized economic–ecological interactions. This approach provides new insights into trade-offs and sustainability dynamics at the micro-watershed level and supports more evidence-based spatial planning and ecosystem management.

2. Materials and Methods

2.1. Research Area

The investigation was located in the Tiworo Watershed, West Muna Regency, Southeast Sulawesi Province, which is roughly 32,636.89 ha in size ([Fig. 1](#) and [Fig. 2](#)). The watershed lies in a tropical climate zone, with an average annual rainfall of around 265.6 mm ([BPS-Statistics Indonesia, Muna Barat Regency 2024a](#)). Ecologically, the Tiworo Watershed serves as a buffer zone, stabilizing agricultural, forestry, and fisheries resources in the western coastal area of

Southeast Sulawesi. As a socio-ecological system, this watershed provides a good focus for studying the impact of land cover change on the provision of ecosystem services, which, in turn, influences the performance of the main economic sectors. This strategic relevance positions the Tiworo Watershed as a crucial landscape for understanding the link between environmental change and regional sector development.

2.2. Research Design and Period Selection

The study reveals that a quantitative observational approach integrating remote sensing-based spatial analysis (remote sensing and GIS) with market-based economic valuation was employed. Analysis periods have been set to 2014, 2019, and 2024 to capture the medium-term dynamics of decadal land-use change and align with the availability of official economic data. 2014 was also selected as the starting point of the analysis because it was the year West Muna Regency was established as a new autonomous region, making it an important reference point for tracing regional development dynamics.

The time period for this change detection was selected based on the radiometric quality of the multisensor imagery and the availability of cloud-free images, thereby ensuring highly reliable results for the spatial analysis (Shafizadeh-Moghadam et al. 2021; Tesfaye et al. 2024). The present study, therefore, constitutes a research design that establishes a firm connection among changes in land cover, the supply of ecosystem services, and the functioning of the economic sectors.

2.3. Data Sources

This study relied heavily on two main data types: spatial and economic. Spatial data were primarily obtained from official Ministry of Environment and Forestry (Kementerian Lingkungan Hidup dan Kehutanan/KLHK) time-series land cover datasets for 2014, 2019, and 2024. Although Landsat 8 OLI/TIRS and Sentinel-2 MSI imagery were preprocessed (atmospheric correction using the dark object subtraction method; median compositing to reduce cloud effects) and classified using random forest (RF) (Bill et al. 2024; Rynkiewicz et al. 2025), these were used only as ancillary validation to check the accuracy of KLHK land cover maps. Ground Control Points (GCPs) from field surveys and high-resolution images further supported validation, ensuring the reliability of the KLHK data.

The RF workflow was not used to generate primary land cover maps; instead, it served to confirm the consistency and reliability of KLHK datasets. The overall classification accuracy target for validation was >85%, in line with standard map validation procedures (Mersha et al. 2024). This approach enabled the study to confidently use the KLHK data as the primary source for subsequent land-cover change analysis while maintaining scientific rigor and reproducibility.

Economic data come from the BPS-Statistics Indonesia of West Muna Regency, specifically the GRDP of the agriculture, forestry, and fisheries sector at constant prices for 2014, 2019, and 2024, supplemented by additional regional sectoral statistics. GRDP serves as a proxy for ecosystem service provision, enabling analysis of the impacts of land-cover change on natural-resource-based economic performance. Spatial and economic data are integrated through GIS overlay and statistical analysis to evaluate trade-offs between land-cover change and primary-sector growth.

To clarify the type, source, and purpose of the data used, Table 1 presents a summary. This table highlights the complementary combination of spatial data (satellite imagery, DEM, and GCP)

and economic data (sectoral GRDP and additional statistics) to address the research objectives. Data selection was carefully carried out, taking into account temporal accessibility, radiometric quality, and the availability of cloud-free imagery to ensure the reliability of the analysis.

Table 1. Summary of research data and data sources

Data type	Specification	Year(s)	Resolution	Source	Purpose / Use
Landsat 8 OLI/TIRS satellite imagery	Multispectral	2014, 2019, 2024	30 m	USGS	Land cover analysis; spatial change trend assessment
Sentinel-2 MSI satellite imagery	Multispectral	2019, 2024	10–20 m	ESA / Copernicus	Detailed land cover analysis; complementary to Landsat
SRTM / CGIAR DEM (Digital Elevation Model)	Elevation data	2014	30 m	USGS / CGIAR	Delineation of Tiworo Watershed boundary; topographic analysis
Ground Control Points (GCPs)	Field control points and high-resolution imagery	2014, 2019, 2024	–	Field surveys; Google Earth / Maxar	Validation of land cover classification
Sectoral GRDP data	Agriculture, Forestry, Fisheries (constant prices)	2014, 2019, 2024	–	BPS-Statistics Indonesia (BPS), West Muna Regency	Proxy for provisioning ecosystem services
Additional sectoral statistics	Agricultural production, fish catch/landings, and forest area	2014, 2019, 2024	–	Relevant local government agencies, West Muna Regency	Cross-check of GRDP; deeper analysis of primary sectors

2.4. Conceptual Framework for Provisioning Ecosystem Services

The study focuses on the provisioning of ecosystem services that yield environmentally sustainable, materially measurable, marketable goods, such as food, timber, and fisheries products (Bimrah et al. 2022). The classification of ecosystem services is from de Hasan et al. (2020), and the economic valuation framework is according to the method of Costanza et al. (2017).

This research mainly concentrates on the ecosystem services that are marketable provisioning directly influenced by ecological changes in watersheds and sectoral economic (agriculture, forestry, and fisheries) performance. At the same time, ecosystem services that do not have a market, like climate regulation, water provision, and cultural values, are still acknowledged as necessary elements of the ecosystem but are not subjected to quantitative analysis in this study.

2.5. Spatial Analysis of Land Cover

Land cover analysis was conducted using official KLHK time-series datasets for 2014, 2019, and 2024. No additional classification was performed; preprocessing was limited to minor corrections where necessary. The reliability of the KLHK data was confirmed through validation using random forest (RF) classification of Landsat 8 OLI/TIRS and Sentinel-2 MSI imagery, supported by ground control points (GCPs) from field surveys with ≥ 50 points per class, targeting an overall accuracy of $>85\%$ (Sun and Ongsomwang 2023).

The area of each land cover class was calculated and reported with confidence intervals to account for classification uncertainty. This approach allowed the identification of the direction and magnitude of land-cover change (e.g., forest and agriculture). It provided the main ecological input

for post-classification comparison, transition matrices, and conversion hotspot maps, ensuring replicability and transparency in the land cover change analysis.

This approach enables the identification of the direction of land-cover change (e.g., forest and agriculture) while quantifying the extent of change with uncertainty estimates (Jasman et al. 2023). Changes in land cover during the 2014–2019–2024 periods were analyzed using post-classification comparison, which yielded not only a transition matrix but also a conversion hotspot map (Aggarwal 2015). These results emphasize spatial changes by indicating the areas of both permanence and change in land cover classes between the periods.

To a large extent, the spatial analysis outcomes serve as the main ecological input for the subsequent trade-off and decoupling analysis using sectoral economic data. Hence, they (the outcomes) lay the groundwork for measuring the interactions between ecological changes in the Tiworo watershed and the behavior of resource-based economic sectors.

2.6. Trade-off Analysis and Potential Decoupling between Ecological Change (Land Cover Change) and Sectoral Economic Growth

This study evaluates local changes in ecological conditions alongside economic growth across sectors, with a specific focus on land degradation and the potential for decoupling. The Tapio decoupling elasticity model measures the elasticity of GRDP growth with respect to land cover change, thereby allowing for absolute decoupling, relative decoupling, coupling/weak decoupling, and negative decoupling (Jing et al. 2024). Initially, the team had to determine the rate of change of the GRDP for the three sectors (agriculture, forestry, and fisheries) in each period using Equation 1.

$$GRDP \text{ growth } (\%) = \frac{Final \text{ GRDP} - Initial \text{ GRDP}}{Initial \text{ GRDP}} \times 100 \quad (1)$$

Next, land cover change was used in Equation 2, assuming that productive land, including forests, mangroves, paddy fields, and shrub/thicket, represents the watershed's ecological capacity. Although shrubs/grasshoppers represent secondary vegetation, recent scientific findings indicate that secondary vegetation can contribute substantially to ecosystem services, including biomass production, soil stabilization, and habitat provision, particularly in tropical landscapes where successional vegetation is common (Smith-Ramirez et al. 2023; Tito et al. 2022).

$$Land \text{ cover change } (\%) = \frac{Final \text{ Area} - Initial \text{ Area}}{Initial \text{ Area}} \times 100 \quad (2)$$

To further examine the robustness of the decoupling results and, at the same time, address any possible bias in defining 'productive land,' a sensitivity test was conducted, where three different scenarios were implemented in defining 'productive land' composition: (i) Composite original (baseline), which includes forest, mangrove forest, paddy field, and shrub/thicket, similar to those in the original analysis; (ii) Forest + mangrove only, where 'productive land' is composed of forest and mangrove forests, without agricultural land and shrub/thicket; and (iii) Mangrove only, where 'productive land' is composed only of mangrove forests, which represents a coastal ecosystem-based indicator.

For these three scenarios, a new value for 'productive land' (E) was computed, while land cover change was still computed using Equation 2. Therefore, the sensitivity test does not alter the original land cover change computation; rather, it tests how different ecological capacities would affect the decoupling results. The Tapio decoupling index (Equation 3) was then applied to each scenario to quantify the elasticity between economic growth and land-cover change. All other

methodological steps—including the calculation of GRDP (Equation 1) and the use of Equations 4–6 for period-specific growth and decoupling—remained unchanged.

The Tapio decoupling elasticity index was adopted to quantify the relationship between ecological evolution and economic development. This formulation represents the elasticity of ecological change relative to economic growth following the standard Tapio decoupling framework. Tapio index is determined by Equation 3 (Regueiro-Ferreira and Alonso-Fernández 2022; Sun et al. 2025).

$$D = \frac{\Delta E / E_0}{\Delta G / G_0} \quad (3)$$

where ΔE and ΔG are the expressions of ecological and economic evolution, E_0 is the baseline productive area, and G_0 is the baseline GRDP.

Classification of D according to Jing et al. (2024), Shang and Luo (2021), and Wang et al. (2023).

- a) Absolute decoupling ($D < 0$): Economic growth is accompanied by a decrease in land degradation or land cover change, indicating watershed development driven by ecological sustainability.
- b) Relative decoupling ($0 \leq D < 0.8$): The economic growth is faster than that of land degradation or land cover change. However, the degradation persists, reflecting improved resource-use efficiency and more rational management.
- c) Coupling/weak decoupling ($0.8 \leq D \leq 1.2$): Economic growth and land cover change are balanced, indicating that the economy remains dependent on ecological pressures in the watershed.
- d) Negative decoupling ($D > 1.2$): The increase in land degradation or land cover change is more rapid than that of economic growth, which is a sign of unsustainable development that needs to be addressed by policy intervention urgently.

By integrating the model, this study not only illustrates the relationship between economic development and nature conservation, but also provides a stronger scientific basis in maintaining the balance between environmental protection and economic development in the agriculture, forestry, and fisheries sectors in the West Muna region, so that nature remains the foundation of local stability.

2.7. Data Curation and Analysis Tools

Information was transformed to the WGS 84 UTM Zone 51S coordinate system for spatial uniformity (Kumar et al. 2024). The unavailable data points were handled using temporal linear interpolation and validated against reputable sources (Moritz et al. 2015). The extreme data points were detected using the interquartile range (IQR) approach, which was validated against primary sources (Dash et al. 2023).

The spatial data analysis was conducted using Google Earth Engine for land cover classification, and the results were analyzed in QGIS 3.30. The statistical tests, such as panel regression, correlation, and Tapio decoupling elasticity, were conducted in R software. In addition, sensitivity analysis was conducted to validate the results. All data transformation, calculations, and analysis processes are fully explained, and the results are shown in **Fig. 1–2** and **Tables 2–6**, where readers can validate the results based on the information provided.

2.8. Ethical Validity

The methods used to conduct these studies are in line with global standards for land use and land cover (LULC) mapping (Brander 2023), decoupling, and ecosystem service assessments (de Groot et al. 2020; Masiero et al. 2019). Secondary data were sourced from publicly available datasets, including time-series land cover data for 2014, 2019 and 2024 (Kementerian Kehutanan Republik Indonesia 2026; KLHK 2025), and from the data provided by the Central Bureau of Statistics of Indonesia (BPS-Statistics Indonesia) – GRDP of the agriculture, forestry, and fisheries sectors for those years. The field data were collected with the permission of the local authorities in accordance with the relevant ethical guidelines for research.

3. Results and Discussion

3.1. Land Cover Change Dynamics and Development Implications in the Tiworo Watershed

Land cover changes in the Tiworo Watershed (32,636.89 ha) over the period 2014–2024 showed marked spatio-temporal variations. These observations over the past decade, divided into two time periods (2014–2019 and 2019–2024), showed high levels of sustainability across dominant land covers, with significant shifts in the environmental balance. Using random forest classification, land cover was classified into major classes: forests, mangrove forests, agricultural lands (rice fields, dry lands), plantations, shrub lands/brush, cultivated ponds, built-up lands, wetlands, bare lands, and water. The accuracy tests confirmed the maps' accuracy (>85%).

The transition matrix for the 2014–2019 time period (**Table 2**) shows that the dominant classes are indeed secondary dryland agriculture (SDA) and shrub/brush (ST). However, there seem to be two major significant land cover (SLC) conversion hotspots, namely (i) forest (F) to dryland agriculture (PDA), which represents the encroachment of agriculture in former F areas, and (ii) mangrove forest (MF) to aquaculture ponds (AP), representing the growing encroachment in mangrove forests due to aquaculture pond development.

Table 2. Land cover transition matrix of Tiworo Watershed (ha) for 2014 and 2019

	F	MF	BU	BL	SDA	PDA	PL	PF	ST	AP	SW	WB
Forest (F)	2,245	1	2	0	0	0	0	0	0	0	0	0
Mangrove forest (MF)	0	410	0	0	0	0	5	0	0	0	0	0
Built-up area (BU)	0	0	390	0	0	0	0	0	0	1	0	0
Bare land (BL)	0	0	0	210	5	0	0	0	1	0	0	0
Secondary dryland agriculture (SDA)	0	0	0	0	20,185	2	0	0	1	0	0	0
Primary dryland agriculture (PDA)	0	0	0	0	0	1,610	0	4	0	0	0	0
Plantation (PL)	0	0	0	0	0	0	220	1	0	0	0	0
Paddy field (PF)	0	0	0	0	0	0	0	450	3	0	0	0
Shrub/thicket (ST)	0	0	0	0	2	0	0	0	6,267	0	0	0
Aquaculture pond (AP)	0	0	0	0	0	0	0	0	0	323	0	0
Swamp/wetland (SW)	0	0	0	0	0	0	0	0	0	0	61	0
Water body (WB)	0	0	0	0	0	0	0	0	0	0	0	25

Regarding the 2019–2024 duration (**Table 3**), the transition trends were generally consistent with past data, but the intensity was accentuated. The built-up area (BU) and aquaculture ponds (AP) increased, but bare lands (BL) fluctuated with preparation and abandonment. However, what is significant is that the mangrove forests (MF) drastically reduced in size from 415.53 ha to 306.77

ha, further accentuating their degradation. However, the forests (F) remained stable at approximately 2,291 ha, indicating resilience in upland areas, while SDA again remained dominant at approximately 20,189 ha.

Table 3. Land cover transition matrix of Tiworo Watershed (ha) for 2019 and 2024

	F	MF	BU	BL	SDA	PDA	PL	PF	ST	AP	SW	WB
Forest (F)		0	0	1	0	0	0	0	0	0	0	0
Mangrove forest (MF)	0		0	0	0	0	6	0	0	0	0	0
Built-up area (BU)	0	0	424	0	0	0	0	0	0	1	0	0
Bare land (BL)	0	0	0	480	0	0	0	0	5	0	0	0
Secondary dryland agriculture (SDA)	0	0	0	0		0	0	0	2	0	0	0
Primary dryland agriculture (PDA)	0	0	0	0	0	1,700	0	2	0	0	0	0
Plantation (PL)	0	0	0	0	0	0	380	0	6	0	0	0
Paddy field (PF)	0	0	0	0	0	0	0	435	3	0	0	0
Shrub/thicket (ST)	0	0	0	0	0	0	0	0	5,972	0	0	0
Aquaculture pond (AP)	0	0	0	0	0	0	0	0	0	420	0	0
Swamp/wetland (SW)	0	0	0	0	0	0	0	0	0	0	31	0
Water body (WB)	0	0	0	0	0	0	0	0	0	0	0	

Note: Cells with no change are shaded/blocked to emphasize only the transitions between classes.

The aggregated change over 2014–2024 (**Table 4**) reveals three important trends: (a) Increase in built-up (from 390.77 to 487.71 ha) and plantation (from 221.51 to 386.38 ha) areas, indicating the spread of human settlement and plantation agriculture, (b) Reduction in mangrove (decreased by 124.84 ha) and wetland (decreased by 30 ha) areas, indicating loss of ecosystem service in coastal and low-lying zones, and (c) No change in the secondary dry land agriculture and forests, which support the agricultural and forestry ecosystem service.

Table 4. Land cover of the Tiworo watershed in 2014, 2019, and 2024

Land cover	Area (ha)		
	2014	2019	2024
Forest (F)	2,248.55	2,286.35	2,291.33
Mangrove forest (MF)	431.61	415.53	306.77
Built-up area (BU)	390.77	424.91	487.71
Bare land (BL)	215.88	485.58	288.13
Secondary dryland agriculture (SDA)	20,188.16	20,189.76	20,190.54
Primary dryland agriculture (PDA)	1,614.00	1,705.79	1,678.08
Plantation (PL)	221.51	238.31	386.38
Paddy field (PF)	453.18	477.69	437.71
Shrub/thicket (ST)	6,269.06	5,973.93	6,288.04
Aquaculture pond (AP)	322.92	339.56	421.00
Swamp/wetland (SW)	60.82	74.08	30.82
Water body (WB)	25.40	25.40	25.40

Source: Ministry of Environment and Forestry of the Republic of Indonesia, 2014, 2019, and 2024 (https://geoportals.menlhk.go.id/server/rest/services/Time_Series/), and author’s analysis results (2025).

The land cover of the Tiworo Watershed is shown in **Fig. 1** and **Fig. 2**. Land cover change analysis in the Tiworo Watershed between 2014 and 2024 reveals significant changes across land classes. Built-up land (BU) or settlement expanded gradually from 390.77 ha in 2014 to 424.91 ha in 2019 and then to 487.71 ha in 2024. On the other hand, mangrove forests (MF) reduced from 431.61 ha to 306.77 ha, along with an increase in aquaculture ponds (AP) from 322.92 ha to 421.00 ha.

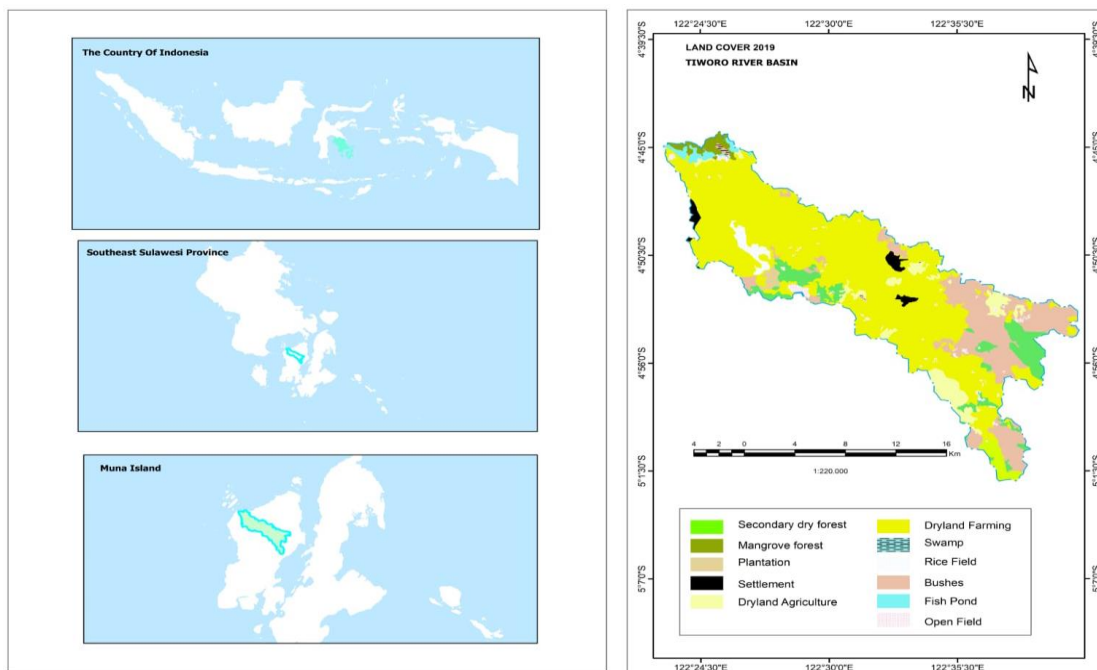


Fig. 1. Land cover of Tiworo Watershed 2019.

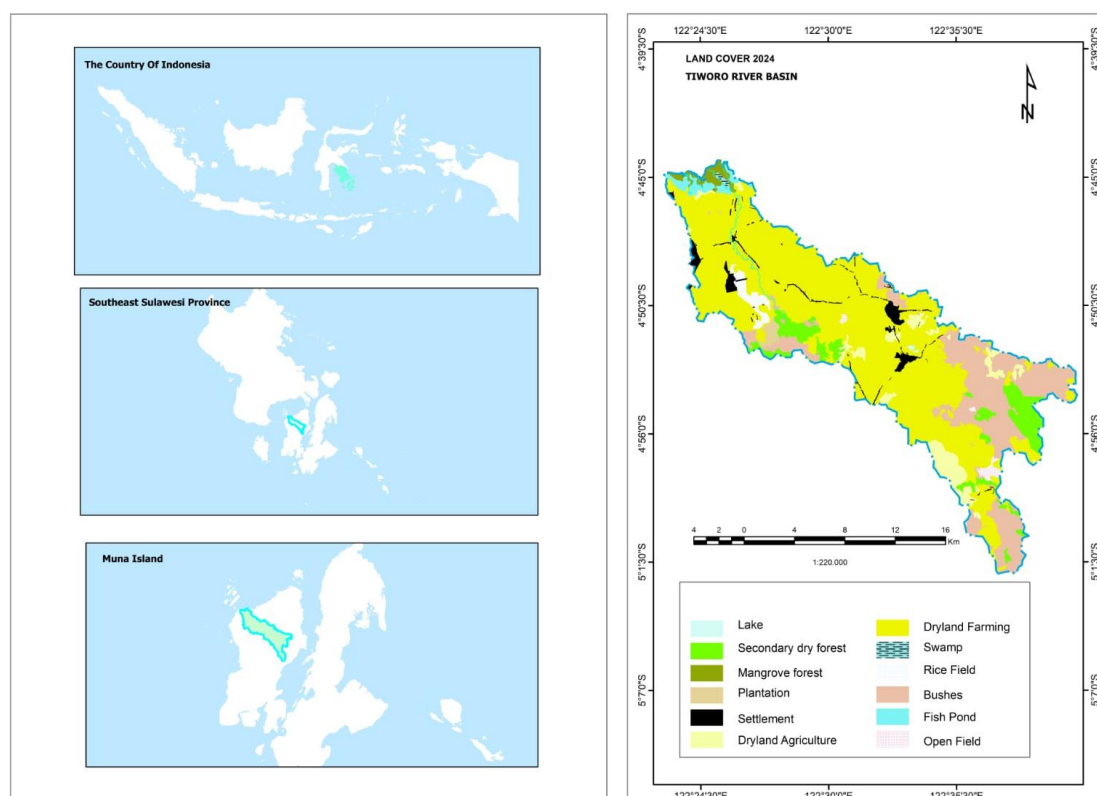


Fig. 2. Land cover of Tiworo Watershed 2024.

Cropland had varied patterns. Paddy (PF) varied irregularly (453.18–477.69–437.71 in ha), and in primary dry land (PDA) grew, then declined (1,614.00–1,705.79–1,678.08 in ha). Secondary dry land (SDA) remained more or less constant at 20,000 ha, and was the major crop land in the catchment. Land under plantations (PL) grew substantially from 221.51 ha to 386.38 ha, and forests (F) moderately from 2,248.55 ha to 2,291.33 ha.

The transitional classes also demonstrated cyclic variation. The bare land (BL) increased significantly in 2019 (from 215.88 to 485.58 ha) but then decreased to 288.13 ha in 2024. The shrub/thicket (ST) class reduced in 2019 (6,269.06–5,973.93 ha) but then again increased in 2024 to 6,288.04 ha. The swamp/wetland (SW) class expanded in 2019 to 74.08 ha, reducing to 30.82 ha in 2024. Water bodies (WB) remained unchanged at 25.40 ha.

On balance, the land cover change patterns in the watersheds show contrast, with stable cores in agricultural and natural habitats juxtaposed with deteriorating marginal habitats such as mangrove forests and wetlands. These patterns reflect growing conflict between economic development and the preservation of natural resources. The analysis presents an opportunity to relate patterns of land-cover change to economic performance within their respective sectors.

3.2. Sectoral Contributions of Agriculture, Forestry, and Fisheries to Regional GRDP

Table 5 illustrates the expansion of the agriculture, forestry, and fisheries (AFF) sector in West Muna Regency from 2014 to 2024 using three primary indicators: GRDP value, sectoral contribution to the regional economy, and annual growth rate.

Table 5. GRDP value, contribution, and growth of the agriculture, forestry, and fisheries sector in West Muna Regency, 2014–2024

The agriculture, forestry, and fisheries sector	2014	2019	2024
GRDP value (billion IDR)	530.70	681.86	851.26
Sector contribution to the regional economy (%)	41.09	38.01	40.40
Economic growth (%)	0.51	5.50	4.39

Source: Central Bureau of Statistics of Muna Regency [BPS] (2025;2024a; 2024b; 2023; 2019).

The AFF industry grew in absolute terms, with output rising from IDR 530.70 billion in 2014 to IDR 681.86 billion in 2019, and then to IDR 851.26 billion in 2024. This confirms the industry's resilience and ability to produce output, even amid annual growth variability.

The sector's contribution was 41.09%, 38.01%, and 40.40% in 2014, 2019, and 2024, respectively. This variance reveals that although the level of contribution was increasing, it was growing at a lower rate compared to the non-primary sectors, but then recovered in 2024 to play a major role in the region's economy.

The growth rate of the AFF sector is strong. Indeed, in 2014, the growth rate was minimal at 0.51%, due to weak productivity during the initial phase of formation. Nonetheless, in 2019, the overall growth rate appreciably increased to 5.50%, largely due to gains in governance and related regional development frameworks, particularly in the Fisheries and Agriculture sub-sectors. However, in 2024, the overall growth rate declined slightly to 4.39%, although this did not diminish the absolute level of GRDP growth; rather, it was due to external factors, such as climatic risks.

The AFF sector continues to be the foundation of the West Muna Regency economy, with a relatively consistent contribution of 38–41% and a consistent increase in GRDP. Nevertheless, the sector's performance is inextricably linked to the integrity of its ecosystem, particularly forests and watersheds, which are instrumental to crop production, fisheries, and timber production. In addition to direct use value (timber, non-timber, and support for agriculture and fisheries), forest ecosystems play a strategic role in preserving economic resilience, as previously demonstrated in economic valuations (Hasddin 2019). Additionally, they contribute to non-use and option values.

These findings underscore the importance of adaptive resource management to safeguard the PKP sector's long-term contribution to regional development.

3.3. Trade-offs and Decoupling Analysis between Ecosystem Change and Sectoral Economic Growth

The trade-off analysis between ecosystem change and economic growth in the Tiworo Watershed was conducted using the Tapio decoupling approach. The first task was to obtain the economic growth rate of GRDP in the agriculture, forestry, and fisheries subsectors for each period (Equation 1). Then, land cover change was calculated, assuming that productive land, consisting of forests, mangroves, rice fields, and shrubs, represents the watershed's capacity. The values obtained from **Table 4** were used to calculate productive land, and percentage changes were then calculated as follows (Equation 2). The Tapio elasticity index (D) was then calculated using the formula (Equation 3). **Table 6** provides a comprehensive overview of the results of the calculation of absolute changes, percentages, and decoupling for the three periods (2014–2019, 2019–2024, and the 2014–2024 aggregation).

Table 6. Absolute change, percentage change, and decoupling elasticity between land area and sectoral economic growth (2014–2024)

Period	Productive Land Area (ha)	Absolute Change ΔE (ha)	ΔE (%)	GRDP (Billion Rp)	Δ GRDP (%)	Decoupling (D)	Result
2014–2019	9,402.41 → 9,153.50	-248.91	-2.65	530.70 → 681.86	28.48	-0.09	Absolute
2019–2024	9,153.50 → 9,323.85	+170.35	+1.86	681.86 → 851.26	24.84	0.07	Relative
2014–2024	9,402.41 → 9,323.85	-78.56	-0.84	530.70 → 851.26	60.40	-0.01	Absolute

The summary of Tapio's analysis results shows three distinct dynamics in the relationship between economic growth and ecological change in the Tiworo River Basin. In the 2014–2019 period, absolute decoupling occurred, with Δ GRDP growth of 28.48% and a relatively small decrease in productive land of -2.65%. Then, in the 2019–2024 period, the decoupling situation shifted to relative decoupling, with Δ GRDP of 24.84% exceeding the degradation of productive land by +1.86%, indicating an increase in land-use efficiency. Cumulatively, over the 2014–2024 period, absolute decoupling was again observed, with a Δ GRDP of 60.40% achieved, accompanied by a very small environmental pressure of -0.84%. The results of this study provide evidence of a trade-off between economic growth and environmental capacity in the Tiworo River Basin.

To further test the robustness of the results, a sensitivity test was conducted using different definitions of productive lands: forest + mangrove and mangrove only. The results revealed that the overall pattern of decoupling remains consistent across all scenarios, with absolute decoupling observed in the periods 2014–2019 and 2014–2024, and relative decoupling observed in the period 2019–2024. Although slight differences in elasticity values were noted, they did not influence the overall classification, indicating that the results were not highly sensitive to the definition of ecological capacity.

3.4. Discussion

Three factors represent the sides of the triangle at the heart of the investigation: a) Change in land cover, b) Economic performance of specific industries, and c) The ecological capacity in

the watersheds of the Tiworo. The results of the current investigation can be utilized in forestry management theory and practice.

Firstly, the secondary dryland agriculture and secondary forests that have been stable over the last ten years showed the resilience of land-based livelihoods, which are still very much dependent on forest ecosystems. Although there have been significant increases in built-up areas and aquaculture, the persistence of secondary forest cover indicates that community land-use practices still have the capacity to maintain ecological functions that support watershed services. This aligns with results from other tropical watersheds, where recovery forests and traditional agricultural systems are considered safeguards against ecological degradation (Admasu et al. 2023; Kiswanto et al. 2025; Mursyid et al. 2025; Samrin et al. 2024; Villareal et al. 2025). These kinds of studies have also found that the core forest and agricultural areas, which are often quite stable, are less susceptible to conversion pressures, whereas the ecosystems on the periphery, such as wetlands and mangroves, are more susceptible (Assefa et al. 2021; Biedemariam et al. 2022; Iskandar et al. 2024; Tarmizi and Rizwan 2024). The shrinking mangrove forests in the Tiworo watershed, primarily due to aquaculture conversion, highlight a trade-off between short-term economic gains and the loss of essential ecosystem services. Such a trend confirms the pattern of results observed across different areas of Southeast Asia (Darmawan and Santoso 2024; Gerona-Daga and Salmo 2022; Hilmi et al. 2023). Based on SLC conversion hotspots, we identify priority zones for mangrove protection and restoration and propose measurable interventions, including (50–100 m) coastal buffer zones, enforcement of local land-use regulations, and community-based mangrove restoration programs (Phan et al. 2020; Velástegui-Montoya et al. 2025).

Second, sectoral GRDP trends by region clearly show that the agriculture, forestry, and fisheries (AFF) sector is the most structurally significant, accounting for 38–41% of the local economy. When disaggregated, the forestry component within the AFF sector reveals how forest management policies, such as selective logging restrictions and mangrove restoration programs, can influence the decoupling pathway between economic growth and ecological pressure. Despite an increase from IDR 530.70 to IDR 851.26 billion, its continuation remains heavily reliant on the ecological health of forests and watershed systems. This aligns with data from Ethiopia and Indonesia, which show that agricultural and fisheries production depends on upstream forest cover and water regulation services (Aneseeye et al. 2022; Jasman et al. 2023; Maladeni et al. 2023; Nugroho et al. 2021; Sarjito et al. 2025). Besides that, ecosystem service valuations highlight that the economic role of the AFF sector is deeply intertwined with the conservation of natural capital (Brander 2023; Mulyana et al. 2024; Rahmadwiati et al. 2021; Ramadhani et al. 2025; Weldemariam et al. 2024). Hence, the sectoral growth pattern of the AFF sector is tightly linked to the forest conservation plan, particularly given their roles in the water cycle, soil fertility, and biodiversity regulation (Budiaman et al. 2025; Lukina et al. 2021).

Thirdly, the Tapio decoupling analysis outlines progressively compromised trade-offs between economic expansion and ecological pressure. The absolute decoupling event in 2014–2019 implies that the initial growth occurred at minimal ecological costs, likely owing to the buffering capacity of the still-forested landscapes. Nevertheless, the shift to relative decoupling in 2019–2024 indicates that, although land-use efficiency has increased, ecological pressures have intensified, especially in mangrove and coastal ecosystems. The results obtained in this paper support the outcomes obtained in global decoupling analysis studies, such as in Xinjiang and in India, in which relative decoupling means the strategy shift in terms of intensification, which increases economic production but also threatens the delicate ecosystems (Jing et al. 2024; Ortega-

Ruiz et al. 2020; Wijaya et al. 2025). According to the Tapio framework, the Tiworo Watershed is at a turning point: growth efficiency is improving, yet ecosystem degradation risks persist.

From a forest management perspective, the continued total loss during the 2014–2024 period is a positive sign, indicating that regional economic growth (+60.40%) has been accompanied by very little ecological degradation (−0.84%). However, the loss of local mangroves and wetlands demonstrates geographic asymmetry in loss, highlighting the need for adaptive management that prioritizes sensitive zones. Lessons learned from watersheds in Ethiopia and Indonesia indicate that asymmetric loss is primarily due to governance issues in ecologically sensitive areas (Admasu et al. 2023; Edison et al. 2025; Nahib et al. 2024; Samrin et al. 2024; Villareal et al. 2025). To support sustainable management, a realistic monitoring plan is proposed that incorporates annual Sentinel-2-based alerts on mangrove loss, community patrols, and licensing controls on aquaculture expansion. In line with sustainable management principles, the loss of irreplaceable natural capital, such as mangrove ecosystems, cannot be fully offset by economic benefits. Therefore, what is needed in cases like this is adaptive management, such as a more rigorous approach to land planning in mangrove ecosystems, or even the evaluation of ecosystem services in forest and regional land planning (Dewi et al. 2024; Sampurno 2023; Ureta et al. 2021).

The results of this study provide empirical and theoretical contributions to forestry and ecological economics. The Tapio decoupling model is valuable for examining the interaction between economic growth and natural capacity at the watershed level, extending the application of decoupling analysis beyond developed countries. The observed shift from absolute to relative decoupling reflects an adaptation phase in land resource management, signaling a conceptual paradigm shift in development considerations in the tropics. In practice, these insights enable the design of land policies that integrate economic development with sustainable nature conservation, promote efficient land use, control land conversion, and support social forestry initiatives.

In conclusion, this study contributes to the understanding of socio-economic factors in watershed and forest management. It provides actionable data on the concept of economic-ecological decoupling in Eastern Indonesia, a region underrepresented in the context of forest sustainability. These findings underscore the importance of cross-sectoral forest governance, sustainable intensification, and community-based conservation. It is recommended to consider incorporating biophysical and socio-political variables to improve decoupling analyses in tropical ecosystems.

4. Conclusions

This research documents the changes in land cover, economic performance of different sectors, and ecological capacity of the Tiworo watershed, which is scenario-based and explained by the Tapio decoupling approach, whereby the main outcomes show that the relation between economic growth and ecological pressure is complicated, nonlinear, and multilayered, where both absolute and relative decoupling phases can indicate an adjustment of land resource management. It strongly reinforces the application of the decoupling concept at the scale of a tropical micro-watershed, which has thus far been tested primarily in developed countries. Theoretically, the findings of this paper constitute a resource-economic ecology of the forest system, providing a new framework for understanding the trade-offs of development in the tropics. On the practical side of the story, other important emphases include adaptive watershed governance through effective land-use planning, halting the conversion of vulnerable ecosystems, and promoting the

development of community forests as a tool for balancing economic productivity with ecological sustainability. It would be highly desirable if future research takes an integrated approach by incorporating several biophysical indicators related to carbon stocks, biodiversity, and forest degradation, in addition to socio-political factors, and includes land tenure security and decentralization to make the disaggregated analysis more robust and a better tool for policy-making in sustainable tropical forest management.

Acknowledgments

The authors would like to thank the Muna Regency Central Statistics Agency for providing the West Muna Regency sectoral GRDP data that served as the basis for this research analysis. Appreciation is also extended to those who provided technical and scientific support in processing land cover data, including random forest-based spatial analysis and evaluation of economic-ecological decoupling. This research would not have been possible without the contributions of fellow researchers and institutions that supported research activities in the Tiworo watershed.

Author Contributions

S.K.: Conceptualization, Methodology, Writing – Original Draft Preparation, Writing – Review and Editing, Supervision; H.: Conceptualization, Methodology, Software, Investigation, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing; L.F.: Conceptualization, Resources, Writing – Review and Editing; A.A.: Methodology, Software, Writing – Review and Editing, Supervision.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

The use of AI in the preparation of this manuscript was limited to basic tools for checking grammar, spelling, referencing, and formatting. No generative or AI-assisted technology was used in the writing, analysis, or interpretation of this research.

References

- Admasu, S., Yeshitela, K., and Argaw, M. 2023. Impact of Land Use Land Cover Changes on Ecosystem Service Values in the Dire and Legedadi Watersheds, Central Highlands of Ethiopia: Implication for Landscape Management Decision Making. *Heliyon* 9(4): e15352. DOI: [10.1016/j.heliyon.2023.e15352](https://doi.org/10.1016/j.heliyon.2023.e15352)
- Aggarwal, C. C. 2015. *Outlier Analysis*. In: Data Mining. Springer, Cham. pp. 237–263. DOI: [10.1007/978-3-319-14142-8_8](https://doi.org/10.1007/978-3-319-14142-8_8)
- Aneseyee, A. B., Soromessa, T., Elias, E., Noszczyk, T., and Feyisa, G. L. 2022. Evaluation of Water Provision Ecosystem Services Associated with Land Use/Cover and Climate Variability in the Winike Watershed, Omo Gibe Basin of Ethiopia. *Environmental Management* 69(2): 367–383. DOI: [10.1007/s00267-021-01573-9](https://doi.org/10.1007/s00267-021-01573-9)
- Assefa, W. W., Eneyew, B. G., and Wondie, A. 2021. The Impacts of Land-Use and Land-Cover Change on Wetland Ecosystem Service Values in Peri-Urban and Urban Area of Bahir Dar City, Upper Blue Nile Basin, Northwestern Ethiopia. *Ecological Processes* 10(1): 39. DOI: [10.1186/s13717-021-00310-8](https://doi.org/10.1186/s13717-021-00310-8)
- Azadi, H., Van Passel, S., and Cools, J. 2021. Rapid Economic Valuation of Ecosystem Services in Man and Biosphere Reserves in Africa: A Review. *Global Ecology and Conservation* 28(3): e01697. DOI: [10.1016/j.gecco.2021.e01697](https://doi.org/10.1016/j.gecco.2021.e01697)

- Bernales, W., Guiritan, F. A. D., Pecato, C. J. L., Mercado, J. A., Tangonan, J. A., Calagui, L. B., and Corbita, V. L. 2025. Community Structure of Mangrove Species in Bagakay Trail Lagoon, Claver, Surigao del Norte, Philippines. *Jurnal Sylva Lestari* 13(3): 812–823. DOI: [10.23960/jsl.v13i3.1193](https://doi.org/10.23960/jsl.v13i3.1193)
- Biedemariam, M., Birhane, E., Demissie, B., Tadesse, T., Gebresamuel, G., and Habtu, S. 2022. Ecosystem Service Values as Related to Land Use and Land Cover Changes in Ethiopia: A Review. *Land* 11(12): 2212. DOI: [10.3390/land11122212](https://doi.org/10.3390/land11122212)
- Bill D. L. M., Biona C. B., and Lemvo M. M. M. 2024. Comparing Sentinel-2 and Landsat 9 for Land Use and Land Cover Mapping Assessment in the North of Congo Republic: A Case Study in Sangha region. *International Journal of Remote Sensing* 45(22): 8015–8036. DOI: [10.1080/01431161.2024.2394238](https://doi.org/10.1080/01431161.2024.2394238)
- Bimrah, K., Dasgupta, R., Hashimoto, S., Saizen, I., and Dhyani, S. 2022. Ecosystem Services of Mangroves: A Systematic Review and Synthesis of Contemporary Scientific Literature. *Sustainability* 14(19): 12051. DOI: [10.3390/su141912051](https://doi.org/10.3390/su141912051)
- BPS-Statistics Indonesia Muna Barat Regency. 2025. *Gross Regional Domestic Product of Muna Barat Regency by Industry 2020–2024*. Badan Pusat Statistik Kabupaten Muna Barat. <<https://munbarkab.bps.go.id/en/publication/2025/04/11/eccc36bac183e6735c8bb98d/produk-domestik-regional-bruto-kabupaten-muna-barat-menurut-lapangan-usaha-2020-2024.html>> (Oct. 2, 2025)
- BPS-Statistics Indonesia, Muna Barat Regency. 2024a. *Monthly Rainfall in Muna Barat Regency (mm), 2023. Statistics of Muna Barat Regency*. <<https://munbarkab.bps.go.id/id/statistics-table/2/MTA1IzI=/jumlah-curah-hujan-menurut-bulan-di-kabupaten-muna-barat.html>> (Sep. 14, 2025)
- BPS-Statistics Indonesia Muna Barat Regency. 2024b. *Gross Regional Domestic Product of Muna Barat Regency by Industry 2019–2023*. Statistics of Muna Regency, Muna Barat, Indonesia. <<https://munbarkab.bps.go.id/en/publication/2024/04/04/67340f36df443c8f8bbf59b4/produk-domestik-regional-bruto-kabupaten-muna-barat-menurut-lapangan-usaha-2019-2023.html>> (Oct. 2 2025)
- BPS-Statistics Indonesia Muna Barat Regency. 2023. *Gross Regional Domestic Product of Muna Barat Regency by Industry 2018–2022*. Statistics of Muna Regency, Muna Barat, Indonesia. <<https://munbarkab.bps.go.id/en/publication/2023/04/05/a9c8d75ad0ddc26cb5624bc8/produk-domestik-regional-bruto-kabupaten-muna-barat-menurut-lapangan-usaha-2018-2022.html>> (Oct. 2, 2025)
- BPS-Statistics Indonesia Muna Barat Regency. 2019. *Gross Regional Domestic Product of Muna Barat Regency by Industry 2014–2018*. Statistics of Muna Regency, Muna Barat, Indonesia. <<https://munbarkab.bps.go.id/id/publication/2019/09/06/912bc4b1023d9c40addb6895/produk-domestik-regional-bruto-kabupaten-muna-barat-menurut-pengeluaran-2014-2018.html>> (Oct. 2, 2025)
- Brander, L. 2023. *Guidance on the economic valuation of ecosystem services and natural capital of the Area (Contract No. ISA/2023/OEMMR002)*. Prepared for the International Seabed Authority. <<https://www.isa.org.jm/wp-content/uploads/2023/11/Guidance-on-economic-valuation-Part-II-of-the-report.pdf>> (Sep. 14, 2025)
- Budiaman, A., Hardjanto, and Natalia, Y. 2025. Cost Analysis of Skyline-Assisted Felling Technique in Private Forests in Probolinggo, Indonesia. *Jurnal Sylva Lestari* 13(1): 21–31. DOI: [10.23960/jsl.v13i1.990](https://doi.org/10.23960/jsl.v13i1.990)

- Costanza, R. 2024. Misconceptions About the Valuation of Ecosystem Services. *Ecosystem Services* 70: 101667. DOI: [10.1016/j.ecoser.2024.101667](https://doi.org/10.1016/j.ecoser.2024.101667)
- Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., and Grasso, M. 2017. Twenty Years of Ecosystem Services: How Far Have We Come and How Far Do We Still Need To Go? *Ecosystem Services* 28(A): 1–16. DOI: [10.1016/j.ecoser.2017.09.008](https://doi.org/10.1016/j.ecoser.2017.09.008)
- Darmawan, A., and Santoso, T. 2024. Mapping Urban Transformation: The Random Forest Algorithm to Monitor Land Use and Land Cover Change in Bandar Lampung City. *Jurnal Sylva Lestari* 12(3): 980–997. DOI: [10.23960/jsl.v12i3.960](https://doi.org/10.23960/jsl.v12i3.960)
- Dash, C. S. K., Behera, A. K., Dehuri, S., and Ghosh, A. 2023. An Outliers Detection and Elimination Framework in Classification Task of Data Mining. *Decision Analytics Journal* 6(2): 100164. DOI: [10.1016/j.dajour.2023.100164](https://doi.org/10.1016/j.dajour.2023.100164)
- de-Groot, R., Brander, L., and Solomonides, S. 2020. *Update of Global Ecosystem Service Valuation Database (ESVD) (FSD Report No. 2020-06, 58 pp.)*. Wageningen, The Netherlands. <https://www.es-partnership.org/wp-content/uploads/2020/08/ESVD_Global-Update-FINAL-Report-June-2020.pdf> (Oct. 2, 2025)
- Dewi, K., Hardian, A. S., and Cahyono, S. A. 2024. Assessing the Economic Value of Water Environmental Services in Mount Merbabu National Park. *Jurnal Sylva Lestari* 12(2): 338–352. DOI: [10.23960/jsl.v12i2.802](https://doi.org/10.23960/jsl.v12i2.802)
- Edison, I., Banuwa, I. S., Yuwono, S. B., Damai, A. A., Hidayat, K. F., Suroso, E., and Hasani, Q. 2025. Institutional Analysis of Sustainable Management of the Sekampung Watershed, Lampung Province, Indonesia. *Jurnal Sylva Lestari* 13(1): 173–189. DOI: [10.23960/jsl.v13i1.1041](https://doi.org/10.23960/jsl.v13i1.1041)
- Faria, D., Morante-Filho, J. C., Baumgarten, J., Bovendorp, R. S., Cazetta, E., Gaiotto, F. A., Mariano-Neto, E., Mielke, M. S., Pessoa, M. S., Rocha-Santos, L., Santos, A. S., Soares, L. A. S. S., Talora, D. C., Vieira, E. M., and Benchimol, M. 2023. The Breakdown of Ecosystem Functionality Driven by Deforestation in A Global Biodiversity Hotspot. *Biological Conservation* 283(3): 110126. DOI: [10.1016/j.biocon.2023.110126](https://doi.org/10.1016/j.biocon.2023.110126)
- García-Rubio, N., Larraz, B., Gámez, M., Raimonet, M., Cakir, R., Sauvage, S., and Sánchez Pérez, J. M. 2024. An Economic Valuation of the Provisioning Ecosystem Services in the South-West of Europe. *Environment, Development and Sustainability* 27(12): 29411–29437. DOI: [10.1007/s10668-024-04877-y](https://doi.org/10.1007/s10668-024-04877-y)
- Gerona-Daga, M. E. B., and Salmo, S. G. III. 2022. A Systematic Review of Mangrove Restoration Studies in Southeast Asia: Challenges and Opportunities for the United Nation’s Decade on Ecosystem Restoration. *Frontiers in Marine Science* 9: 987737. DOI: [10.3389/fmars.2022.987737](https://doi.org/10.3389/fmars.2022.987737)
- Hasan, S. S., Zhen, L., Miah, M. G., Ahamed, T., and Samie, A. 2020. Impact of Land Use Change on Ecosystem Services: A Review. *Environment Development* 34(768): 100527. DOI: [10.1016/j.envdev.2020.100527](https://doi.org/10.1016/j.envdev.2020.100527)
- Hasddin, H. 2019. Valuasi Ekonomi Sumberdaya Alam pada DAS Tiworo Kabupaten Muna Barat. *Akrab Juara: Jurnal Ilmu-Ilmu Sosial* 4(2): 115–125. DOI: [10.58487/akrabjuara.v4i2.592](https://doi.org/10.58487/akrabjuara.v4i2.592)
- Hilmi, N., Benitez Carranco, M. B., Broussard, D., Mathew, M., Djoundourian, S., Cassotta, S., Safa, A., Maliki, S., Descroix-Comanducci, F., Allemand, D., Berthomieu, C., Hall-Spencer, J. M., and Ferrier-Pagès, C. 2023. Tropical Blue Carbon: Solutions and Perspectives for

- Valuations of Carbon Sequestration. *Frontiers in Climate* 5: 1169663. DOI: [10.3389/fclim.2023.1169663](https://doi.org/10.3389/fclim.2023.1169663)
- Imran, Z., Ketjulan, R., and Masahiro, Y. 2021. Sustainable Strategy on Marine Spatial Planning of Tiworo Archipelagic. *Jurnal Ilmu dan Teknologi Kelautan Tropis* 13(3): 379–394. DOI: [10.29244/jitkt.v13i3.35311](https://doi.org/10.29244/jitkt.v13i3.35311)
- Iskandar, B., Saidah, Kurnia, A.A., Jauhari, A., and Zannah, F. 2024. Modeling Land Cover Change using MOLUSCE in Kahayan Tengah Forest Management Unit, Central Kalimantan, Indonesia. *Jurnal Sylva Lestari* 12(2): 242–257. DOI: [10.23960/jsl.v12i2.865](https://doi.org/10.23960/jsl.v12i2.865)
- Jasman, J., Syarif, M., Juharsah, Syarif, S. A., Ngii, E., and Hasddin. 2023. Model of the Linkage between Land Cover Changes to Water Discharge and Food Productivity: The Case of the Konawehea Watershed in Indonesia. *Journal of the Geographical Institute “Jovan Cvijic”, SASA* 73(2): 169–185. DOI: [10.2298/ijgi2302169m](https://doi.org/10.2298/ijgi2302169m)
- Jing, L., Zhou, B., and Liao, Z. 2024. Decoupling Analysis of Economic Growth and Carbon Emissions in Xinjiang Based on Tapio and Logarithmic Mean Divisia Index Models. *Sustainability* 16(18): 8010. DOI: [10.3390/su16188010](https://doi.org/10.3390/su16188010)
- Kasim, S., Astuti, T., Agarwal, A., Hasddin, H., Fariki, L., Sulistiyono, N., Rustam, L. O., Asizah, N., Saranani, F., and Ahmad. 2024. Economic Value of Forest Ecosystems in the Nipa-Nipa Grand Forest Park, Southeast Sulawesi, Indonesia. *Biodiversitas* 25(11): 4292–4303. DOI: [10.13057/biodiv/d251129](https://doi.org/10.13057/biodiv/d251129)
- Kiswanto, M., Gunawan, I. A., Nurrachmawati, A., Pramono, D. A., and Widyasasi, D. 2025. Spatiotemporal Detection of Land Cover Dynamics in Forests and Food Sources in Supporting the Nusantara Capital City of Indonesia. *Jurnal Sylva Lestari* 13(2): 422–440. DOI: [10.23960/jsl.v13i2.1098](https://doi.org/10.23960/jsl.v13i2.1098)
- Kementerian Kehutanan Republik Indonesia. 2026. *Luas rekalkulasi penutupan lahan di Indonesia*. Statistik Kehutanan. <https://statistik.kehutanang.go.id/statistic/show/luas-rekalkulasi-penutupan-lahan-di-indonesia> (Sep. 30, 2026)
- KLHK-Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia. 2025. *Statistik Kehutanan*. <https://statistik.kehutanang.go.id> (Apr. 30, 2025)
- Kumar, P., Choudhary, A., Kumar, R. P., Kumar, P., and Kumar, G. 2024. Comprehensive Geospatial Mapping and Monitoring of An Eastern Coalfield in India. *Discover Geosciences* 2(1): 32. DOI: [10.1007/s44288-024-00039-9](https://doi.org/10.1007/s44288-024-00039-9)
- Latifah, S., Gandaseca, S., Afifi, M., Prasetyo, A. R., Purnama, M. I., Kertalam, L. R. A., and Pratama, R. P. 2025. Three Decades of Forest Biomass Estimation in Southeast Asia: A Systematic Review of Field, Remote Sensing, and Machine Learning Approaches (1995–2025). *Jurnal Sylva Lestari* 13(3): 728–746. DOI: [10.23960/jsl.v13i3.1162](https://doi.org/10.23960/jsl.v13i3.1162)
- Lukina, N. V., Geraskina, A. P., Gornov, A. V., Shevchenko, N. E., Kuprin, A. V., Chernov, T. I., Chumachenko, S. I., Shanin, V. N., Kuznetsova, A. I., Tebenkova, D. N., and Gornova, M. V. 2021. Biodiversity and Climate-Regulating Functions of Forests: Current Issues and Research Prospects. *Forest Science Issues* 1(4): 1–60. DOI: [10.31509/2658-607x-202141k-60](https://doi.org/10.31509/2658-607x-202141k-60)
- Maladeni, E. S., Hasddin, H., and Jasman, O. O. H. 2023. Monitoring of River Water Discharge Volume in the Konawehea Watershed, Southeast Sulawesi Province, Indonesia. *International Journal of Recent Engineering Science* 10(5): 24–29. DOI: [10.14445/23497157/ijres-v10i5p103](https://doi.org/10.14445/23497157/ijres-v10i5p103)

- Masiero, M., Pettenella, D., Boscolo, M., Barua, S. K., Animon, I., and Matta, J. R. 2019. Valuing Forest Ecosystem Services: A Training Manual for Planners and Project Developers. *Forestry Working Paper* No. 11, pp. 216. FAO, Rome.
- Mersha, E., Degefa, S., Argaw, M., and Mengist, W. 2024. Impact of Land Use Land Cover Changes on Ecosystem Service Values: Implication for Landscape Management. *Journal of Landscape Ecology* 18(1): 61–85. DOI: [10.2478/jlecol-2025-0004](https://doi.org/10.2478/jlecol-2025-0004)
- Moritz, S., Sardá, A., Bartz-Beielstein, T., Zaefferer, M., and Stork, J. 2015. Comparison of Different Methods for Univariate Time Series Imputation in R. *arXiv preprint arXiv:1510.03924*. DOI: [10.48550/arxiv.1510.03924](https://doi.org/10.48550/arxiv.1510.03924)
- Msofe, N. K., Sheng, L., Li, Z., and Lyimo, J. 2020. Impact of Land Use/Cover Change on Ecosystem Service Values in the Kilombero Valley Floodplain, Southeastern Tanzania. *Forests* 11(1): 109. DOI: [10.3390/f11010109](https://doi.org/10.3390/f11010109)
- Mulyana, B., Polgár, A., and Vityi, A. 2024. Forest Carbon Modeling in Poplar and Black Locust Short Rotation Coppice Plantation in Hungary. *Jurnal Sylva Lestari* 12(2): 324–337. DOI: [10.23960/jsl.v12i2.883](https://doi.org/10.23960/jsl.v12i2.883)
- Mursyid, H., Suryanto, P., Fadhillah, S., Silmia, B., and Wibowo, F. A. C. 2025. Diversity and Ecophysiological Performance of Coffee Under Dry-Field and Homegarden Agroforestry in Yogyakarta. *Jurnal Sylva Lestari* 13(1): 75–89. DOI: [10.23960/jsl.v13i1.1005](https://doi.org/10.23960/jsl.v13i1.1005)
- Nahib, I., Wahyudin, Y., Widiatmaka, W., Ambarwulan, W., Amhar, F., Suwedi, N., Darmawan, M., Suryanta, J., Pranoto, B., Ramadhani, F., Nugroho, N. P., Cahyana, D., and Karolinoerita, V. 2024. Evaluating the Effects of Changes in Land Use and Assessing the Value of Ecosystem Services in the Cisadane Watershed, Banten Province, Indonesia. *Journal of Infrastructure, Policy and Development* 8(6): 3788. DOI: [10.24294/jipd.v8i6.3788](https://doi.org/10.24294/jipd.v8i6.3788)
- Nugroho, P., Rahayu, A.D., Juliani, R., Indarto, Cahyo, A.D., Ankhoviyya, N., Gumilar, E., Susanto, D., and Nugroho, A. 2021. Understanding Resident Intention and Behavior Toward Water Conservation Initiative in the Upstream of West Java, Indonesia. *Jurnal Sylva Lestari* 10(1): 12–25. DOI: [10.23960/jsl.v10i1.541](https://doi.org/10.23960/jsl.v10i1.541)
- Ortega-Ruiz, G., Mena-Nieto, A., and García-Ramos, J. E. 2020. Is India on the Right Pathway to Reduce CO₂ Emissions? Decomposing an Enlarged Kaya Identity using the LMDI Method for the Period 1990–2016. *Science of the Total Environment* 737: 139638. DOI: [10.1016/j.scitotenv.2020.139638](https://doi.org/10.1016/j.scitotenv.2020.139638)
- Phan, T. N., Kuch, V., and Lehnert, L. W. 2020. Land Cover Classification using Google Earth Engine and Random Forest Classifier—The Role of Image Composition. *Remote Sensing* 12(15): 2411. DOI: [10.3390/rs12152411](https://doi.org/10.3390/rs12152411)
- Pulido, R. L., Casendac, E. F., Rozano, M. J., Jandug, C. M., Obo, L., Sabado, J. M., Elvira, M., and Corbita, V. 2025. Assessment of Mangrove Species Diversity in the Municipality of Nasipit, Agusan del Norte, Philippines. *Jurnal Sylva Lestari* 13(3): 761–773. DOI: [10.23960/jsl.v13i3.1192](https://doi.org/10.23960/jsl.v13i3.1192)
- Rahmadwiati, R., Wicaksono, R.L., and Apriyanto, D. 2021. Estimation and Economic Valuation of Above-Ground Carbon in Forest Area with the Special Purpose of Gunung Bromo, Karanganyar, Central Java, Indonesia. *Jurnal Sylva Lestari* 10(1): 116–126. DOI: [10.23960/jsl.v10i1.548](https://doi.org/10.23960/jsl.v10i1.548)

- Ramadhani, N., Wicaksono, R. L., and Rahmadwiati, R. 2025. Carbon Storage Potential and Economic Valuation in the Arboretum of Forest Area with Special Purpose (KHDTK) Aek Nauli, Indonesia. *Jurnal Sylva Lestari* 13(1): 234–247. DOI: [10.23960/jsl.v13i1.1057](https://doi.org/10.23960/jsl.v13i1.1057)
- Regueiro-Ferreira, R. M., and Alonso-Fernández, P. 2022. Ecological Elasticity, Decoupling, and Dematerialization: Insights from the EU-15 study (1970–2018). *Ecological Indicators* 140(3): 109010. DOI: [10.1016/j.ecolind.2022.109010](https://doi.org/10.1016/j.ecolind.2022.109010)
- Rynkiewicz, A., Hościło, A., Aune-Lundberg, L., Nilsen, A. B., and Lewandowska, A. 2025. Detection and Quantification of Vegetation Losses with Sentinel-2 Images using Bi-Temporal Analysis of Spectral Indices and Transferable Random Forest Model. *Remote Sensing* 17(6): 979. DOI: [10.3390/rs17060979](https://doi.org/10.3390/rs17060979)
- Sampurno, D. 2023. *Integrated Spatial Ecosystem Services Valuation Approach with Community Participation in a Social Forestry Scheme*. In Okamoto, M., Osawa, T., Prasetyawan, W., and Binawan, A. (Eds.). *Local Governance of Peatland Restoration in Riau, Indonesia*. Springer. pp. 261–286. DOI: [10.1007/978-981-99-0902-5_12](https://doi.org/10.1007/978-981-99-0902-5_12)
- Samrin, S., Millang, S., Ridwan, and Daud, M. 2024. Land Productivity and Land Equivalent Ratio of Agroforestry System in Marena Customary Forest, Enrekang Regency, South Sulawesi Province, Indonesia. *Jurnal Sylva Lestari* 12(2): 532–548. DOI: [10.23960/jsl.v12i2.877](https://doi.org/10.23960/jsl.v12i2.877)
- Sari, I. L., Weston, C. J., Newnham, G. J., and Volkova, L. 2021. Assessing Accuracy of Land Cover Change Maps Derived from Automated Digital Processing and Visual Interpretation in Tropical Forests in Indonesia. *Remote Sensing* 13(8): 1446. DOI: [10.3390/rs13081446](https://doi.org/10.3390/rs13081446)
- Sarjito, J., Budiastuti, M. T. S., Hidayat, A., Yuswantoro, I. E., and Wintanti, R. A. S. 2025. The Effectiveness of Forest Management and Monitoring Implementation Under the National Forest Stewardship Standards (NFSS) Scheme in Indonesia. *Jurnal Sylva Lestari* 13(2): 467–484. DOI: [10.23960/jsl.v13i2.1133](https://doi.org/10.23960/jsl.v13i2.1133)
- Shafizadeh-Moghadam, H., Khazaei, M., Alavipanah, S. K., and Weng, Q. 2021. Google Earth Engine for Large-Scale Land Use and Land Cover Mapping: An Object-Based Classification Approach using Spectral, Textural and Topographical Factors. *GIScience and Remote Sensing* 58(6): 914–928. DOI: [10.1080/15481603.2021.1947623](https://doi.org/10.1080/15481603.2021.1947623)
- Shang, M., and Luo, J. 2021. The Tapio Decoupling Principle and Key Strategies for Changing Factors of Chinese Urban Carbon Footprint Based on Cloud Computing. *International Journal of Environmental Research and Public Health* 18(4): 2101. DOI: [10.3390/ijerph18042101](https://doi.org/10.3390/ijerph18042101)
- Smith-Ramírez, C., Grez, A., Galleguillos, M., Cerda, C., Ocampo-Melgar, A., Miranda, M. D., Muñoz, A. A., Rendón-Funes, A., Díaz, I., Cifuentes, C., Alaniz, A., Seguel, O., Ovalle, J., Montenegro, G., Saldes-Cortés, A., Martínez-Harms, M. J., Armesto, J. J., and Vita, A. 2023. Ecosystem Services of Chilean Sclerophyllous Forests and Shrublands on the Verge of Collapse: A Review. *Journal of Arid Environments* 211(71): 104927. DOI: [10.1016/j.jaridenv.2022.104927](https://doi.org/10.1016/j.jaridenv.2022.104927)
- Sun, J., and Ongsomwang, S. 2023. Optimal Parameters of Random Forest for Land Cover Classification with Suitable Data Type and Dataset on Google Earth Engine. *Frontiers in Earth Science* 11: 1188093. DOI: [10.3389/feart.2023.1188093](https://doi.org/10.3389/feart.2023.1188093)
- Sun, W., Huo, Z., and Zhang, S. 2025. Dissertation Title: Decoupling Analysis of Building Carbon Emissions and Economic Growth Based on Tapio Model and EKC Curve. *Carbon Balance and Management* 20(1): 63. DOI: [10.1186/s13021-025-00349-6](https://doi.org/10.1186/s13021-025-00349-6)

- Tarmizi, N.M., and Rizwan, N.I. 2024. Integrated Supervised Classification of LULC in Identifying Musang King Durian Illegal Farming Location. *Jurnal Sylva Lestari* 12(2): 459–479. DOI: [10.23960/jsl.v12i2.856](https://doi.org/10.23960/jsl.v12i2.856)
- Taufik, T., Mukaddas, J., and Hasddin, H. 2021. Tingkat Perubahan Tutupan Lahan (Deforestasi) di DAS Tiworo Kabupaten Muna Barat. *Sang Pencerah: Jurnal Ilmiah Universitas Muhammadiyah Buton* 7(2): 260–270. DOI: [10.35326/pencerah.v7i2.1106](https://doi.org/10.35326/pencerah.v7i2.1106)
- Tesfaye, W., Elias, E., Warkineh, B., Tekalign, M., and Abebe, G. 2024. Modeling of Land Use and Land Cover Changes Using Google Earth Engine and Machine Learning Approach: Implications for Landscape Management. *Environmental Systems Research* 13(1): 31. DOI: [10.1186/s40068-024-00366-3](https://doi.org/10.1186/s40068-024-00366-3)
- Tito, R., Salinas, N., Cosio, E. G., Boza Espinoza, T. E., Muñiz, J. G., Aragón, S., Nina, A., and Roman-Cuesta, R. 2022. Secondary Forests in Peru: Differential Provision of Ecosystem Services Compared to Other Post-Deforestation Forest Transitions. *Ecology and Society* 27(3): 12. DOI: [10.5751/es-13446-270312](https://doi.org/10.5751/es-13446-270312)
- Tunda, A., Malamassam, D., Soma, A. S., and Sudia, L. B. 2025. Dynamics of Land Cover Change on Hydrological Conditions using The Soil and Water Assessment Tool Model in the Tiworo Watershed. *Ecological Engineering and Environmental Technology* 26(2): 14–26. DOI: [10.12912/27197050/196400](https://doi.org/10.12912/27197050/196400)
- Ulqodry, T. Z., Raihan, M., Muhtadi, Sarno, Hendri, M., Apri, R., Putri, W. A. E., and Aryawati, R. 2025. Carbon Stock and Potential for Carbon Absorption by Mangrove Forests on Maspari Island: The Outermost Small Island in South Sumatra. *Jurnal Sylva Lestari* 13(2): 519–536. DOI: [10.23960/jsl.v13i2.1095](https://doi.org/10.23960/jsl.v13i2.1095)
- Ureta, J. C., Clay, L., Motallebi, M., and Ureta, J. 2021. Quantifying the Landscape’s Ecological Benefits—An Analysis of the Effect of Land Cover Change on Ecosystem Services. *Land* 10(1): 21. DOI: [10.3390/land10010021](https://doi.org/10.3390/land10010021)
- Utomo, A. A. W., Kamarudin, N., Samdin, Z., Razali, S. M., and Adibah, R. 2025. Land Use Mapping of Areas with Intense Socio-Economic Activities using Integrated Unmanned Aerial Vehicle and Geographic Information System. *Jurnal Sylva Lestari* 13(3): 824–848. DOI: [10.23960/jsl.v13i3.1217](https://doi.org/10.23960/jsl.v13i3.1217)
- Velasco-Munoz, J. F., Aznar-Sánchez, J. A., Schoenemann, M., and López-Felices, B. 2022. The Economic Valuation of Ecosystem Services: Bibliometric Analysis. *Oeconomia Copernicana* 13(4): 977–1014. DOI: [10.24136/oc.2022.028](https://doi.org/10.24136/oc.2022.028)
- Velástegui-Montoya, A., Brito-Matamoros, R., Jaya-Montalvo, M., Caiza-Morales, L., Adami, M., Morante-Carballo, F., and Carrión-Mero, P. 2025. Land Use Change and Mangrove Conservation Strategies in the Gulf of Guayaquil, Ecuador through spatial and Delphi-Based Analysis. *Discover Applied Sciences* 7(10): 1121. DOI: [10.1007/s42452-025-07761-0](https://doi.org/10.1007/s42452-025-07761-0)
- Villareal, J.F., Poclis, C.E., Sindatok, A.R.N., De Vera, P.J.D., Santiago-Arenas, R.D., and Limbona, B.H.N.M. 2025. Rapid Assessment of Trees and Shrubs in Sifaran Watershed, Maguindanao Island, Philippines: Implications for Watershed Conservation. *Jurnal Sylva Lestari* 14(1): 1–15. DOI: [10.23960/jsl.v14i1.1253](https://doi.org/10.23960/jsl.v14i1.1253)
- Wang, X., Zhao, X., Zhang, S., Shi, S., and Zhang, X. 2023. Decoupling Effect and Driving Factors of Land-Use Carbon Emissions in the Yellow River Basin using Remote Sensing Data. *Remote Sensing* 15(18): 4446. DOI: [10.3390/rs15184446](https://doi.org/10.3390/rs15184446)

- Weldemariam, E. M., Geleto, S. D., Argaw, M., and Mengist, W. 2024. Impact of Land Use Land Cover Changes on Ecosystem Service Values: Implication for Landscape Management. *Journal of Landscape Ecology* 18(1): 61–85. DOI: [10.2478/jlecol-2025-0004](https://doi.org/10.2478/jlecol-2025-0004)
- Wijaya, B. A., Riniarti, M., Hidayat, W., Prasetya, H., Yoo, J., and Park, B. B. 2025. Field Evaluation of Biochar Application on the Early Growth of *Falcataria moluccana*: Effects of Pyrolysis Temperatures and Biochar Application Rates. *Jurnal Sylva Lestari* 13(1): 248–263. DOI: [10.23960/jsl.v13i1.1134](https://doi.org/10.23960/jsl.v13i1.1134)