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Critical Land Planning Low Emission Development Strategy in Bila Riven Basin of South Sulawesi Province

Sultan[1*], Khaifah Asgaf[2], Sri Ade Putra[3], Muthmainnah[1], Mukhlis[4]

[1] Department of Forestry, Faculty of Agriculture, Universitas Muhammadiyah Makassar, Makassar, Indonesia.
[2] Department Animal Science, Science and Technology Faculty, Universitas Islam Negeri Alauddin Makassar, Makassar, Indonesia.
[3] Department of Forestry, Faculty of Agriculture and Forestry, Universitas Sulawesi Barat, Majene, Indonesia.
[4] Agribusiness Study Program, Department of Agriculture Business, Politeknik Pertanian Negeri Payakumbuh, Lima Puluh Kota, Indonesia.

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Corresponding Author:
Sultan
ijlalsultan93@gmail.com

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Abstract: Environmental degradation in the Bila Watershed, characterized by increasing critical land, carbon emissions, erosion, and sedimentation in Lake Tempe, requires integrated low-emission land-use planning. This study aims to analyze carbon stocks, carbon dioxide (CO_2) sequestration, sedimentation, and economic valuation under several land-use scenarios using the Land Use Planning for Low Emission Development Strategy (LUWES) approach. The novelty of this study lies in the integration of critical land analysis, carbon stock estimation, sedimentation assessment, and economic valuation into low-emission watershed planning scenarios. The research was conducted in the Bila Watershed, South Sulawesi Province, covering an area of 179,612.87 ha during the 2016–2017 period. Biomass measurements were conducted using nested plots across representative land-cover classes, while erosion was estimated using the Universal Soil Loss Equation (USLE) and sedimentation was calculated using the Sediment Delivery Ratio (SDR) approach. Economic feasibility was analyzed using the Net Present Value (NPV) method. Three land-use scenarios were simulated over a 20-year planning horizon. The results indicate that the existing condition produced carbon emissions of 915,537.49 tons CO_2-eq and estimated sedimentation of 396,163.05 tons/year. Scenario I provided the best ecological-economic balance by increasing carbon stocks, reducing erosion and sedimentation by 45.93%, and increasing economic value by 10.66%. Scenario II generated the highest economic return but increased ecological pressure, while Scenario III emphasized social forestry and emission reduction with moderate economic benefits. These findings demonstrate that integrated low-emission watershed planning can support critical land rehabilitation, climate change mitigation, and sustainable watershed management.

Keywords: Bila watershed; Carbon stock; CO_2 emissions; Economic valuation; Land use; Sedimentation

Introduction

The use of natural resources, particularly forests in watersheds (DAS), plays a vital role in sustaining life, both directly and indirectly. Direct benefits of forests include timber, non-timber forest products, and wildlife, while indirect benefits include environmental services, aesthetic functions, watershed water management, oxygen supply, and carbon sequestration (Kawasi, 2024). Carbon absorption in forests occurs through photosynthesis, where plants absorb CO_2 from the atmosphere and water from the soil to produce oxygen and carbohydrates, which are then stored in the form of biomass as carbon reserves.

However, the exploitation of forests, land, and water beyond the carrying capacity of the watershed has caused forest and critical land damage due to unplanned logging, encroachment, logging, and other forms of degradation. This condition triggers deforestation, resulting in increased flooding during the rainy season

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and drought during the dry season, erosion and sedimentation, silting of rivers, reservoirs, and dams, and disruption to irrigation systems, power generation, and transportation (Santos et al., 2021; Nurdin et al., 2022; Melania & Prasetyo, 2025). As a result, the watershed's carrying capacity for ecosystems and human activities continues to decline.

Forest damage in watersheds also has a global impact by increasing greenhouse gas emissions due to reduced vegetation's ability to absorb CO_2, thereby contributing to climate change and global warming (Pamungkas et al., 2023; Pamungkas et al., 2025). Forests are the largest carbon sinks in the global carbon cycle and can store up to ten times more carbon than other types of vegetation, so that forest degradation directly reduces the indirect benefits of these forests.

Watersheds are complex ecological systems involving various biophysical, social, economic, and institutional factors. Their management faces not only technical challenges but also cross-sectoral planning, organizational, and management issues. In Indonesia, most watersheds are in critical condition, characterized by frequent floods, droughts, and landslides, as well as the expansion of critical land (Kurniawan et al., 2025). Based on the Decree of the Minister of Forestry No. SK.328/Menhut-II/2009, there are 108 priority watersheds that require serious attention. The area of critical national land shows significant year-to-year dynamics, in line with the high rate of deforestation, making Indonesia a major contributor to global greenhouse gas emissions.

This condition shows that the watershed planning and management system implemented to date has not been effective in responding to political, social, economic, institutional, and technological dynamics, including the implications of regional autonomy (Hertasning et al., 2022). The natural watershed area often does not align with government administrative boundaries, even though ecologically, the watershed is a unified system from upstream to downstream, connected through the hydrological cycle.

Based on these conditions, this study focuses on a low-emission critical land planning strategy in the Bila watershed using the Land Use Planning for Low Emission Development (LUWES) approach, which is a key difference from previous research. This approach is important, given that the majority of people in the Bila watershed live in rural areas near forests and are highly dependent on land and agriculture for their livelihoods (Daka, 2024). Land management planning must consider the watershed's biophysical conditions, stakeholders' interests, and the safeguarding of indigenous communities' tenure rights. In addition to mitigating climate change by increasing carbon storage and sequestration, other environmental services, such as hydrological functions and biodiversity, must be maintained.

This research was conducted in the Bila Watershed, a national priority watershed with an area of 179,612.59 hectares that crosses Enrekang, Sidrap, and Wajo Regencies. The Bila Watershed serves as the primary source of water for agricultural irrigation and domestic needs, with its headwaters in Enrekang Regency and its outlet at Lake Tempe (Suwardji et al., 2021). Land cover conditions indicate a predominance of dryland agriculture mixed with shrubs, while forest cover only covers about 23% of the watershed area. The level of critical land in the Bila watershed is relatively high, exacerbated by very high levels of erosion and sedimentation in most areas.

These conditions indicate that human activities inconsistent with the land's carrying capacity have increased greenhouse gas emissions and sedimentation in downstream areas, particularly Lake Tempe. Therefore, new models and approaches to watershed management are needed that can accommodate the trade-offs inherent to various critical land-use planning scenarios for low-emission development (Suparwata, 2018). Considering the complexity of the Bila watershed system, this research was conducted through a phased analysis, including analysis of biophysical and socio-economic subsystems, analysis of critical land changes in the last five years based on Geographic Information Systems (GIS), and integration of carbon data with the LUWES approach to formulate a low-emission critical land planning scenario in the Bila watershed.

The increase in the area of critical land in the Bila watershed, from 8,609 ha (4.79%) in 2010 to 36,696 ha (20.43%) in 2012, indicates an ecological imbalance in the watershed system that has resulted in a decline in the ability of forest vegetation to absorb carbon dioxide (CO_2) and increased greenhouse gas (GHG) emissions in the region. This condition is exacerbated by the main problems in planning low-emission critical land, namely overlapping land uses, weak integration of planning and licensing implementation, and a lack of integration between land uses within a watershed landscape (Rajagukguk, 2025). Therefore, land management planning in the Bila Watershed needs to be carried out in an integrated manner by involving stakeholders and supported by adequate data, information, and analysis tools, so that the research problem is focused on the large area of critical land and the carbon emissions that occur, as well as the formulation of low-emission critical land management planning scenarios in the Bila Watershed.

The results of this study are expected to provide benefits to the government and stakeholders in the development of low-emission critical land-based development as part of the implementation of Government Regulation of the Republic of Indonesia

Number 37 of 2012 concerning Watershed Management, Law of the Republic of Indonesia Number 37 of 2014 concerning Soil and Water Conservation, as well as the implementation of REDD/REDD+ and the National Action Plan for Reducing Greenhouse Gas Emissions, particularly in the Bila Watershed and Indonesia in general (Yulianingrum et al., 2019). Scientifically, this research enriches the knowledge regarding low-emission critical land planning in the Bila Watershed and encourages further studies related to the issue of critical land and carbon emissions; in terms of development, it becomes a consideration in the preparation of criticality-based land use planning to support low-emission development and improve the asynchronous planning and implementation of permits; and in terms of society, it supports the improvement of farmers' welfare through the implementation of optimal and sustainable land use scenarios that provide added value to the management of the land they cultivate.

The scope of this research is focused on formulating critical land planning scenarios in order to support the implementation of the Government Regulation of the Republic of Indonesia Number 37 of 2012 concerning River Basin Management and the mandate of the Law of the Republic of Indonesia Number 37 of 2014 concerning Soil and Water Conservation, which emphasizes that land and water are non-renewable natural resources and are vulnerable to degradation due to geographical conditions and utilization that is not in accordance with their function, designation, and carrying capacity so that they need to be protected, restored, improved, and maintained (Faris Risal Ramadhan et al., 2024). In addition, this research includes planning for low-emission critical land to support the REDD/REDD+ implementation framework in Indonesia as well as national and regional policies related to reducing greenhouse gas emissions, including Presidential Regulation of the Republic of Indonesia Number 71 of 2011 concerning the Implementation of the National Greenhouse Gas Inventory, Presidential Regulation of the Republic of Indonesia Number 61 of 2011 concerning the National Action Plan for Reducing Greenhouse Gas Emissions, and Regional Action Plans for Reducing Greenhouse Gas Emissions, with reference to the Regulation of the Minister of Environment of the Republic of Indonesia Number 15 of 2013 concerning Measurement, Reporting, and Verification of Climate Change Mitigation Actions as a guideline to produce accurate, transparent, and accountable planning and achievements of climate change mitigation actions.

The novelty of this research lies in the application of a new approach in the critical land planning strategy in the Bila Watershed, which not only considers the carbon emission aspect but also the economic feasibility of the land in supporting the implementation of the National Action Plan and Regional Action Plan for Reducing Greenhouse Gas Emissions, especially in the forestry and agriculture sectors. This research adapts the Land Use Planning for Low Emission Development Strategy (LUWES) approach by adding variables of land criticality level and economic feasibility in the land economic analysis, so that the formulated land use scenarios can be prioritized for handling and tested for their economic feasibility, as a basis for implementing an applicable and sustainable low emission critical land planning strategy in the Bila Watershed.

The novelty of this research lies in the integration of critical land assessment, carbon stock estimation, sedimentation analysis, and economic valuation into a low-emission watershed land-use planning framework using the LUWES approach. Previous studies generally focused only on land degradation, carbon emissions, or economic aspects separately, whereas this study simultaneously evaluates ecological and economic trade-offs under different land-use scenarios. In addition, this study modifies the LUWES approach by incorporating land criticality levels and economic feasibility indicators into scenario simulations, thereby providing a more comprehensive basis for sustainable watershed management and climate change mitigation planning in the Bila Watershed.

Method

This research is based on land planning and is classified as non-experimental research using a survey method. Data were analyzed using spatial analysis with an overlay technique (overlapping map sheets) based on existing attributes, in the form of a Bila Watershed administration map, a land cover/use map, a forest area map, a land suitability map, a rainfall map, a soil type map, and a slope map.

The data sources in this study consist of primary and secondary data (Sugiyono, 2018; Mukhlis et al., 2019; Mukhlis et al., 2024). Primary data were obtained through satellite image interpretation for the preparation of land cover/use maps, interviews related to community economic activities, field observations of land use, and measurements of biomass and carbon stocks in land units representing land use classes, which were selected purposively (Asgaf et al., 2025) based on accessibility. Secondary data were obtained from literature studies and related agencies regarding the general conditions of the research location, including administrative maps of the Bila Watershed, forest area maps, land capability class maps, spatial pattern maps of the South Sulawesi RTRW, soil type maps, slope maps, rainfall data, and population data.

The data collection procedures in this study include biophysical and socioeconomic data. Biophysical data were collected to obtain information on land conditions, land unit arrangement, land criticality assessment, land use changes, and carbon stocks, which include data on land cover, productivity, management, erosion factors (R, K, LS, C, and P), rainfall, soil type, and slope gradient, analyzed with the help of GIS. Land use change data were obtained by interpreting Landsat imagery in 2001 and 2016, which were verified through field surveys (ground checks). Carbon stock measurements were carried out based on aboveground biomass using a tiered plot method (20x20 m to 2x2 m), with non-destructive measurements using allometric equations and destructive methods for understory plants, and supported by secondary data from various previous studies. Socioeconomic data were obtained through interviews with respondent farmers using a stratified random sampling method and secondary statistical data covering population, livelihoods, income, land ownership, farming patterns, wage levels, and prices. All spatial and non-spatial data are then compiled to form land planning units, which serve as the basis for land use change scenarios.

Data analysis techniques were conducted through spatial, quantitative, and economic approaches. Spatial analysis of critical land was conducted using an overlay method of various critical land-determining parameters, including land cover, slope gradient, erosion hazard level, productivity, and management, based on forestry regulations, in the UTM coordinate system, and a scoring method to produce a classification of land criticality levels. The erosion hazard level was calculated using the Universal Soil Loss Equation (USLE) with factors R, K, LS, C, and P, which were then used to estimate sediment yield. Land planning units were constructed by compiling RTRW data, area status, permits, and critical land using GIS analysis, then analyzed for changes in land cover/use through interpretation of Landsat imagery from 2001 and 2016, classification accuracy tests, spatial overlays, and land change matrices. Carbon stocks and emissions were calculated using the stock-difference approach, based on biomass measurements, carbon content calculations, CO_2 absorption, and differences in carbon stocks between land uses. Economic aspects were analyzed using Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR) to assess the feasibility of the land-use system. Next, emission-reduction scenarios and 20-year land-use change simulations were developed and analyzed using trade-off analysis to select the best scenario based on carbon emissions, economic benefits, land-use reductions, and sedimentation.

Result and Discussion

Critical Land in the Bila River Basin

Determining critical land in a watershed (DAS) is calculated by assigning each parameter determining critical land a score based on the area type. These scores are then summed. The summed scores are then classified according to area type to determine the level of critical land.

Table 1. Land Criticality Level in the Bila Watershed

Critical Level	Areas	Total	%			
	APL (ha)	HL (ha)	HP (ha)	HPT (ha)		
Somewhat Critical	54,406.78	1,182.94	-	-	55,589.72	30.95
Critical	31,213.32	12,212.13	-	12.44	43,437.89	24.18
Critical Potential	11,965.93	34,102.37	2,063.58	5,250.18	53,382.06	29.72
Very Critical	26,141.93	464.98	46.44	27.83	26,681.17	14.85
Not Critical	-	184.9	184.91	152.22	522.03	0.29
Total	123,727.95	48,147.32	2,294.93	5,442.67	179,612.87	100

Source: GIS analysis results, 2017

Based on Table 1, the level of critical land in the Bila Watershed, the area of critical land in the Protected Forest is dominated by critical potential of 34,102.37 ha and critical of 12,212.13 ha. Production forests and limited production forests are still dominated by a critical potential of 2,063.58 ha and a very critical potential of only 46.44 ha; land conditions in the critical and somewhat critical categories are not found in the Production Forest area.

Other use areas are the largest areas in the Bila watershed, dominated by slightly critical areas of 54,406.78 ha, critical areas of 31,213.32 ha, very critical areas of 26,141.93 ha, and critical potential areas of 11,965.93 ha. In general, the critical land area in the Bila watershed is slightly critical, 55,589.72 ha (30.95%), critical 43,437.89 ha 24.18 ha, critical potential 53,382.06 ha (29.72%), very critical 26,681.17 ha (14.85%) and the Bila watershed area in non-critical condition is only 522.03 ha or 0.29% of the total Bila watershed area of 179,612.87 ha. Based on these conditions, the Bila Watershed is one of the critical watersheds in Indonesia, requiring management and restoration to improve its carrying capacity and function optimally. The level of land criticality in the Bila Watershed in graphic form can be seen in Figure 1.

The function of a watershed is a combined effect carried out by all factors within it, namely vegetation, topography, soil, and humans. If any one of these factors changes, it will also affect the watershed ecosystem. Changes in the ecosystem will also disrupt the watershed's function, resulting in an abundance of water during the rainy season and a very low water supply during the dry season (Ayushinta et al., 2023). The alternating natural disasters of floods and droughts that occur in the Bila watershed area are one of the impacts of the watershed failing to carry out its function as a reservoir, storage and distribution of water to rivers, in addition to this, it will have an impact on the downstream part of the Bila watershed, namely the sustainability of the Tempe Lake ecosystem as the estuary of the rivers that flow in the Bila watershed (Shafira et al., 2021).

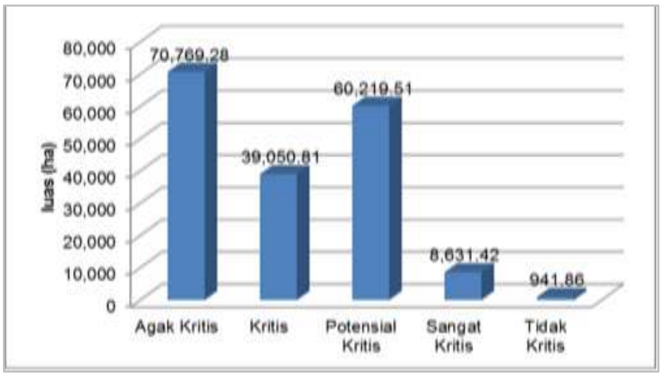

Figure 1. Graph of land criticality level in the bila watershed

Sediment yield calculations are an additional analysis to determine the sediment potential resulting from the high erosion levels in the Bila watershed, which flows into Lake Tempe. Sediment yield is calculated using the equation (Ulumuddin, 2019):

$$Y = E(SDR)Ws \tag{1}$$

Information:
Y : Sediment yield per unit area
E : Total erosion (tons/year)
SDR : Sediment Release Ratio
Ws : Watershed area (ha)

The SDR value is obtained by Eq (Asdak, 2010):
SDR = 0,41 A -0,3
Information:
SDR : Sediment Release Ratio
A : Watershed area (179,612.87 ha)

So the SDR value is:
SDR = 0.41x179,612.87-0.3 = 0.01088 ha
It is known:
E : 36,412,119.01 tons/year
Ws : 179,612.87 ha
SDR : 0.01088 ha

Then the sediment value is:
Y = 36,412,119.01 X 0.01088 X 179,612.87
Y = 71,025,325,247.63 tons/year

Based on the results of the sediment measurements, it is estimated that the sediment stored in Lake Tempe is 71,025,325,247.63 tons/year, which ultimately affects the effective depth of Lake Tempe and causes an increase in the surface water of Lake Tempe.

Sedimentation is the process of deposition/accumulation of soil particles, which causes shallowing of river channels and river estuaries as a result of the erosion process (Saputra et al., 2020). These soil particles are washed to a lower location, usually a river or sea estuary. This can cause shallowing in river channels or estuaries.

Sedimentation is one of the main problems in the Bila watershed. Sedimentation increases significantly every year. Major rivers in the surrounding area have become shallow, even in certain areas, particularly the lower reaches of the Bila River, where they are almost level with residential areas (Imat et al., 2025). This indicates that sedimentation in this watershed is significant and dangerous, as it could threaten businesses and the safety of surrounding communities at any time. Furthermore, this event can damage existing transportation infrastructure such as roads, bridges, and other facilities. The main roads around the river are severely damaged, with some roads impassable to vehicles (Wentasari & Lisa, 2024). Given that this sedimentation problem has affected various community activities and development in this area, it is necessary to immediately take concrete steps to improve the watershed's condition.

Carbon Reserves and Absorption of Various Types of Land Cover in the Bila Watershed

Carbon stocks per hectare in various land cover classes were determined based on aboveground biomass, litter, and soil organic matter, which were estimated using allometric equations that had been developed and validated by previous researchers; field biomass measurements were conducted in primary forests, secondary forests, shrubs, and savannas, while other land use types used secondary data from the Directorate General of Forestry Planning, with the type of land cover/use and the average value of carbon stocks of the Bila Watershed presented in Table 2.

Table 2. Types of Land Cover/Use and Average Value of Watershed Carbon Stocks

Land use/cover	carbon (tons/ha)	Biomass (tons/ha)
Primary Forest	198.33	421.97
Secondary Forest	90.31	192.23
Settlement	4.1*	8.72
Dryland Farming	8*	17.02
Dry Land Farming Mixed with Bushes	44.96	95.65
Savannah	6.37	13.62
Ricefield	5**	10.64
Shrubs	7,82	16.68
Open Land	3.4*	7.23
Swamp Thicket	43**	91.49
Body of water	0	0
Mixed Forest (Village Forest)	90.31	192.23
MIXED FOREST (HKM)	90.31	192.23
HTR	64**	136.17
Similar Forests (People's Forests)	64**	136.17
Intensive Reforestation	90.31	192.23
Palm Oil Plantation	40**	85.11
Coffee Agroforestry	28**	59.57
People's Plantations	63**	134.04

Source: processed primary data, 2017

* Direktorat jenderal Palanologi Kehutanan, 2010

** Harja et al. (2001)

Primary Forest

In the primary forest, 26 species were identified at the tree level, dominated by Calophyllum sp., Heritiera trifoliata, Lithocarpus celebica, Palaquium sp., Planchonella sp., Prunus arborea, and Syzygium sp.; at the pole level, there were 18 species dominated by Castanopsis sp., Lithocarpus sp., Litsea sp., Prunus arborea, and Syzygium sp., while the sapling level consisted of 32 species dominated by Syzygium lineatum, Sloetia elongata, Pternandra caerulescens, Heritiera javanica, and Garcinia celebica, and the understory was dominated by Heritiera trifoliata, Gironniera subequalis, and Syzygium sp.; The average biomass per hectare of each stratum was 295.83 tons (trees), 69.17 tons (poles), 49.33 tons (saplings), 2.73 tons (understory), and 4.91 tons (litter), so that the total primary forest biomass reached 421.97 tons/ha, with the largest contribution coming from the tree stratum.

Primary forest carbon stocks are calculated based on the total vegetation biomass obtained from the allometric equation with the assumption that 44.6% of biomass is stored carbon (SNI 7724, 2011), resulting in an average carbon stock per hectare of 139.04 tons in the tree strata, 32.51 tons in the pole strata, 23.18 tons in the sapling strata, 1.28 tons in the understory (vegetation with a diameter of <10 cm and a height of <1.5 m such as herbs, shrubs, epiphytes, lianas, and grasses), and 2.31 tons in litter, with a total primary forest carbon stock reaching 198.33 tons/ha.

The CO_2 uptake of primary forests was calculated based on the annual biomass growth obtained from the allometric equation (coefficients a and b) and converted by a factor of 1.4667 (SNI 7724, 2011), resulting in an average uptake per hectare per year of 14.46 tons in the tree strata, 5.07 tons in the pole strata, 23.72 tons in the sapling strata, 2.11 tons in the undergrowth, and 2.96 tons in the litter, with a total primary forest CO_2 uptake of 49.52 tons/ha/year.

Secondary Forest

Secondary forest biomass was obtained from vegetation observation results which showed that at the tree level there were 11 species dominated by guava, sugar palm (Arenga pinnata), white teak (Gmelina arborea), and jabon (Anthocepalus cadamba), while at the pole level it was dominated by guava, white teak, and cadamba, and at the sapling level it was dominated by rattan; the measurement results showed an average biomass of 127.54 tons/ha in the tree strata, 31.16 tons/ha in the pole, 27.65 tons/ha in the sapling, 1.61 tons/ha in the undergrowth, and 4.24 tons/ha in the litter, so that the total secondary forest biomass reached 192.23 tons/ha, with the largest contribution coming from the tree strata.

Secondary forest carbon stocks were calculated from the total vegetation biomass obtained through the allometric equation (coefficients a and b) with the assumption that 44.6% of the biomass is stored carbon (SNI 7724, 2011), so that the average carbon stocks were obtained respectively of 59.94 tons/ha in tree strata, 14.64 tons/ha in poles, 12.99 tons/ha in saplings, 0.75 tons/ha in understory plants (vegetation with a diameter of <10 cm and a height of <1.5 m such as herbs, shrubs, epiphytes, lianas, and grasses), and 1.99 tons/ha in litter, which consists of the remains of dead plants on the forest floor, with a total secondary forest carbon stock of 90.31 tons/ha.

Secondary forest CO_2 uptake was calculated based on the total annual biomass growth of vegetation obtained from the allometric equation (coefficients a and b) and converted using a factor of 1.4667 (SNI 7724, 2011), resulting in an average uptake of 9.18 tons/ha/year in tree strata, 5.62 tons/ha/year in poles, 4.75 tons/ha/year in saplings, 2.37 tons/ha/year in understory plants, and 2.11 tons/ha/year in litter, with a total secondary forest carbon dioxide uptake of 24.03 tons/ha per year.

Mixed Shrub Dry Land Agriculture

In agricultural land (mixed plantations), 10 species were identified at the tree level, 6 species at the pole level, and 8 species at the sapling level, with dominant species including langsat, clove, durian, mango, and rambutan; biomass measurements were carried out on vegetation with a height of ≥ 1.5 m and a diameter of ≥ 10 cm using plots representing diameter classes, and the results showed an average biomass of 48.23 tons/ha in the tree strata, 38.84 tons/ha in the pole strata, and 8.58 tons/ha in the sapling strata, so that the total biomass of agricultural land reached 95.65 tons/ha, with the largest contribution coming from the tree strata.

Carbon stocks in agricultural land containing forestry plants were calculated from the total vegetation biomass using allometric equations with the assumption that 47% of the biomass is stored carbon, and the results showed that the average carbon stocks were 22.67 tons/ha in the tree strata, 18.26 tons/ha in the pole strata, and 4.03 tons/ha in the sapling strata, so that the total carbon stocks of agricultural land reached 44.96 tons/ha with the largest contribution coming from the tree strata.

CO_2 uptake in agricultural land (mixed gardens) was calculated from annual biomass growth using an allometric equation converted by a factor of 1.4667, and the results showed an average uptake of 3.83 tons/ha/year in the tree strata, 3.82 tons/ha/year in the pole strata, and 7.73 tons/ha/year in the sapling strata, so that the total CO_2 uptake reached 15.38 tons/ha/year; the high contribution of perennial/woody plants in the mixed garden system confirms its role as the main carbon store compared to annual agricultural crops, in line with the findings of Pati et al. (2022) and Adinugroho et al. (2023) who reported that mixed garden carbon reserves reached 62.34 tons/ha or equivalent to CO_2 uptake of 228.79 tons/ha.

Shrubs

The shrub cover type dominated by Melastoma vegetation has an average total biomass of 16.68 tons/ha, consisting of 13.22 tons/ha of shrub biomass and 3.46 tons/ha of litter, indicating that the shrub strata are the main contributor of biomass to the shrub ecosystem.

Carbon stocks in shrubs were determined by drying samples, weighing biomass, and converting to carbon using a factor of 0.47 (SNI 7724, 2011), with the results showing that carbon stocks came from shrubs of 6.2 tons/ha and litter of 1.62 tons/ha, so that the total average carbon stocks in the shrub cover type reached 7.82 tons/ha.

Carbon dioxide uptake in shrubs was calculated by multiplying the biomass by a conversion factor of 1.4667 (SNI 7724, 2011), which resulted in an average uptake of 4.45 tonnes/ha per year in the shrub strata and 1.25 tonnes/ha per year in the litter, so that the total potential CO_2 uptake in the shrub cover type reached 5.7 tonnes/ha per year.

Savannah

Based on observations of the savanna cover type, the most dominant vegetation and the one that plays a role in ecological control is cogongrass, with an average biomass of 13.62 tons/ha, or 5.45 kg/plot, reflecting the characteristics of the grassland community at the research location.

Carbon reserves in the savanna cover type were determined by drying and weighing biomass samples, which were then converted into carbon using a factor of 0.47 (SNI 7724, 2011), with a biomass yield of 5.45 kg/plot producing 2.55 kg/plot of carbon, or equivalent to an average carbon reserve of 6.37 tons/ha in savanna grasslands.

Carbon dioxide absorption in the savanna cover type was calculated by multiplying the annual biomass of 1.39 kg/plot by a conversion factor of 1.4667 (SNI 7724, 2011), resulting in CO_2 absorption of 2.03 kg/plot or equivalent to 5.07 tons/ha per year, which reflects the average carbon dioxide absorption potential of savanna grasslands at the research location.

Critical and Low Emission Land Planning Scenarios

The opportunity cost in reducing carbon and CO_2 emissions from the land sector is defined as the value of the economic benefits lost due to choosing certain land use alternatives to reduce emissions, while the opportunity cost of increasing carbon and CO_2 sequestration/absorption is the value of the economic benefits obtained from land use alternatives that increase carbon absorption; both values are measured using the Net Present Value (NPV) approach, namely the accumulated difference between income and expenditure that has been discounted over a certain period, both in the actual land use system and in the designed scenario.

Opportunity Cost First Scenario (I)

Based on the projection of the first scenario (I), the total economic benefit value of the land use system increases from the actual condition of IDR 50,725,292,557,325 to IDR 56,131,412,675,886 or an increase of 10.66%, so that the opportunity cost in the form of economic benefits from increased sequestration/absorption of carbon and CO_2 reaches Rp 5,406,119,531,124 which comes from the Mixed Forest system (Village Forest), Similar Forests (People's Forest and People's Plantation Forest), Dryland Agriculture, Intensive Reforestation, and Rice Fields, while the opportunity cost of carbon and CO_2 emissions is negative at IDR –1,079,851,818,602 which reflects the loss of economic benefits due to the conversion of Dryland Agriculture land mixed with Shrubs, Shrubs, and Open Land/vacant land.

Opportunity Cost Second Scenario (II)

In the second scenario (II), the total economic benefit value of the land use system increased from IDR 50,725,292,557,325 to IDR 62,507,284,407,462 or an increase of 23.23% from the actual condition, so that the opportunity cost in the form of economic benefits from increased sequestration/absorption of carbon and CO_2 reached IDR 11,781,991,850,137 originating from settlements, dryland agriculture, intensive reforestation, rice fields, mixed forests (HKm), HTR, community plantations, oil palm plantations, and coffee agroforestry, while the opportunity cost of carbon and CO_2 emissions was negative at IDR –4,230,282,562,038 which reflected the loss of economic benefits due to the conversion of swamp scrub, secondary dryland forest, mixed dryland agriculture with shrubs, shrubs, open land/vacant land, and savanna.

Opportunity Cost Scenario Three (III)

In the third scenario (III), the total economic benefit value of the land use system increased from IDR 50,725,292,557,325 to IDR 51,598,259,423,371 or an increase of 1.27% from the actual condition, so that the opportunity cost in the form of economic benefits due to increased sequestration/absorption of carbon and CO_2 amounted to IDR 872,966,866,046 originating from Mixed Forests (HKm), HTR, and Mixed Forests (Village Forests), while the opportunity cost of carbon and CO_2 emissions was negative at IDR –506,547,309,656 which indicated the loss of economic benefits due to the conversion of dryland agriculture mixed with shrubs, bushes, open land/empty land, and savanna.

The sediment value resulting from erosion in the Bila watershed is the estimated annual accumulation of erosion reaching Lake Tempe. The simulation results of three land-use change scenarios show decreases in erosion and sedimentation, with varying magnitudes, as summarized in Table 3.

Table 3. Erosion and Sediment Results Before and After the Land Use Change Direction Scenario

Description	Erosion (tons/year)	Sedimentation (tons/year)	Erosion Change (tons/year)	Sedimentation Change (tons/year)	Percentage (%)
Current	36,412,119	71,025,325,248	0	0	0
Scenario I	19,686,327	38,400,066,408	16,725,792	32,625,258,839	45.93
Scenario II	30,292,582	59,088,583,174	6,119,537	11,936,742,074	16.81
Scenario III	27,526,802	53,693,664,410	8,885,317	17,331,660,838	24.40

Source: Analysis Results, 2017

The erosion and sedimentation values in the land use guidelines show significant changes, where Scenario I reduces erosion and sediment by 16,725,792 tons/year and 32,625,258,839 tons/year or 45.93% of the actual conditions, Scenario II by 6,119,537 tons/year and 11,936,742,074 tons/year or 16.81%, and Scenario III by 8,885,317 tons/year and 17,331,660,838 tons/year or 16.81%, so that Scenario I is the most effective because it maintains the function of forests, settlements, swamp scrub, and dryland agriculture and converts non-vegetation and open land into tree-based land and forests through intensive reforestation; Conceptually, erosion control is carried out by covering the land surface with crowns and litter and increasing infiltration to reduce surface runoff (Banuwa, 2013).

By translating the low-emission critical land development planning into three scenarios and their respective simulations, projections of emissions, economic benefits, critical land area, and sedimentation of Lake Tempe in the future were obtained, as well as the opportunity cost value due to emissions and benefits from sequestration, so that the trade-off analysis showed that the highest carbon reserves were in Scenarios I and III (the lowest in Scenario II), the effectiveness of reducing emissions and increasing sequestration was highest in Scenario I, while the economic benefits and total opportunity cost were most profitable in Scenario II, and the best performance in reducing critical land and sedimentation was also achieved by Scenario I which reduced critical land from 24.18% to 15.47% (down 8.71%) and sedimentation by 45.93% from actual conditions.

Scenario I is the most effective and balanced alternative because it is able to significantly reduce critical land, sedimentation, and carbon emissions while increasing carbon stocks and absorption and the value of economic benefits through strategies to maintain forests, settlements, swamp scrub, and dryland agriculture and convert non-vegetated land to tree and forest-based cover, resulting in the best ecological-economic performance; as an alternative, Scenario III based on social forestry also reduces erosion and carbon emissions with economic benefits that are still higher than actual conditions and in line with the target of the Social Forestry Program of 12.7 million ha and mitigation of 29% emission reduction by 2030, which emphasizes the importance of balancing ecological and economic functions in sustainable land use planning.

Each land use scenario has a different ecological-economic-emission trade-off, where Scenario I excels in carbon reserves and sequestration, low critical land and sedimentation but with lower benefit values and opportunity costs than Scenario II, Scenario II maximizes benefit values and opportunity costs but produces the lowest carbon reserves and the highest emissions, critical land, and sedimentation, while Scenario III based on social forestry produces the lowest emissions and better ecological performance than Scenario II but with the lowest carbon reserves, benefit values, and opportunity costs; therefore, the selection of scenarios for the implementation of low-emission critical land development planning in the Bila Watershed (Enrekang, Sidrap, and Wajo Regencies) must be adjusted to regional conditions and stakeholder interests within the framework of the National Action Plan (RAN) and the Regional Action Plan (RAD) for reducing greenhouse gas emissions.

Conclusion

The Bila Watershed is dominated by slightly critical land (30.95%), while critical and very critical land account for 24.18% and 14.85%, respectively, indicating severe watershed degradation. Land-use changes during 2001–2016 contributed to carbon emissions of 915,537.49 tons CO_2-eq and estimated sedimentation reaching 396,163.05 tons/year in Lake Tempe. Among the three simulated scenarios, Scenario I provided the most balanced ecological and economic performance through increased carbon stocks, reduced erosion and sedimentation, and improved economic benefits. The novelty of this research lies in integrating critical land assessment, carbon stock analysis, sedimentation estimation, and economic valuation into low-emission watershed planning using a modified LUWES approach. This integrated framework provides practical implications for watershed rehabilitation policies, low-emission development planning, and climate change mitigation strategies, particularly in priority watersheds in Indonesia. This study has several limitations, including assumptions used in land-use scenario simulations, limited temporal land-use data, and socioeconomic variables that were not dynamically modeled. Future studies are recommended to incorporate climate variability, hydrological modeling, and stakeholder-based socioeconomic dynamics to improve low-emission watershed planning.

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S.T.: Developing ideas, analyzing, writing, reviewing, responding to reviewers' comments; K.A., S.A.P., M.M.: analyzing data, overseeing data collection, reviewing scripts, and writing; M.K.: reviewing and writing scripts.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Adinugroho, W. C., Krisnawati, H., Imanuddin, R., Anwar, C., Weston, C. J., & Volkova, L. (2023). Developing biomass allometric equations for small trees in mixed-species forests of tropical rainforest ecozone. *Trees, Forests and People*, *13*(August), 1–11. https://doi.org/10.1016/j.tfp.2023.100425

Asdak, C. (2010). *Hidrologi dan Pengelolaan Daerah Aliran Sungai*. Gadjah Mada University Press.

Asgaf, K., Hifizah, A., Astati, Ananda, S., Jamili, M. A., & Mukhlis. (2025). Application of Fermented Feed Technology to Improve Beef Cattle Business Efficiency and Student Agribusiness Learning. *Jurnal Penelitian Pendidikan IPA*, *11*(5), 604–610. https://doi.org/10.29303/jppipa.v11i5.11135

Ayushinta, R. D., Herlambang, S., Arbiwati, D., & Maswar, M. (2023). Hubungan Kematangan Gambut Dengan Kadar Lengas Terhadap Emisi Karbon Dioksida (CO2) Pada Gambut Kalimantan Tengah. *Jurnal Tanah Dan Air (Soil and Water Journal)*, *18*(1), 11. https://doi.org/10.31315/jta.v18i1.9471

Banuwa, I. S. (2013). *Erosi*. Kencana.

Daka, M. D. (2024). Analisis Tingkat Emisi Gas Rumah Kaca Pada Lahan Sawah Kabupaten Sragen Tahun 2019 (Sebagai Bahan Pengayaan pada Pembelajaran Geografi SMA KD 3.6. Menganalisis Dinamika Atmosfer dan Dampaknya Terhadap Kehidupan). *Geadidaktika*, *4*(1), 84. https://doi.org/10.20961/gea.v4i1.64028

Hertasning, B., Samudra, A. A., Satispi, E., Manullang, O. R., Dharmowijoyo, D. B. E., & Wibowo, A. W. (2022). Strategi Zonasi Penggunaan Kendaraan Bermotor dengan Pendekatan Zona Parkir Progresif dan Zona Rendah Emisi dalam Mewujudkan Kota Ramah Lingkungan. *Jurnal Penelitian Transportasi Darat*, *24*(2), 119–126. https://doi.org/10.25104/jptd.v24i2.2175

Imat, A., & Santosa, W. (2025). Pengaruh Faktor Risiko Terhadap Kinerja Logistik: Studi Kasus Rantai Pasok Liquified Natural Gas di Perusahaan Floating Storage and Regasification Unit di Indonesia. *Jurnal Locus Penelitian Dan Pengabdian*, *4*(10), 9709–9721. https://doi.org/10.58344/locus.v4i10.4896

Kawasi, B. (2024). Pemetaan Program Kegiatan Penurunan Emisi Gas Rumah Kaca di Provinsi Kepulauan Riau 2023–2025. *Jurnal Archipelago*, *3*(02). https://doi.org/10.69853/ja.v3i02.143

Kurniawan, F., Ardiansyah, M., & Anwar, S. (2025). Perkiraan Emisi GRK Berbasis Perubahan Penggunaan Lahan Pada Pola Ruang Pulau Rupat. *Jurnal Ilmu Tanah Dan Lingkungan*, *27*(2), 123–130. https://doi.org/10.29244/jitl.27.2.123-130

Melania, S. D., & Prasetyo, C. P. (2025). Analisis Lahan Kritis Menggunakan Sistem Informasi Geografis di DAS Bendung Kuncir Kabupaten Nganjuk. *Jurnal Tecnoscienza*, *9*(2), 199–212. https://doi.org/10.51158/eh63s806

Mukhlis, M., Ismawati, I., Sillia, N., Fitrianti, S., Ukrita, I., Wisra, R. F., Raflis, H., Hendriani, R., Hanum, L., Ibrahim, H., Nofianti, S., Marta, A., & Sari, N. (2024). Characteristics of Production Factors and Production of Zero Tillage System Rice Farming. *Jurnal Penelitian Pendidikan IPA*, *10*(8), 6013–6019. https://doi.org/10.29303/jppipa.v10i8.8542

Mukhlis, Noer, M., Nofialdi, & Mahdi. (2019). Analysis of income and feasibility of rice-cattle integration system farming based on enterprises scale. *Journal of Advanced Research in Dynamical and Control Systems*, *11*(7), 544–553. Retrieved from https://www.jardcs.org/abstract.php?id=2678

Nurdin, I., Lihawa, F., & Koem, S. (2022). Pemetaan lahan kritis menggunakan sistem informasi geografis di kecamatan sumalata provinsi gorontalo. *Geodika: Jurnal Kajian Ilmu Dan Pendidikan Geografi*, *6*(2), 232–243. https://doi.org/10.29408/geodika.v6i2.6531

Pamungkas, H. S. R., Syahrulyati, T., Manfiqri, M. D., Yogaswara, L. M., & Halimatusyadiah, S. (2025). Riview Dan Inventarisasi Lahan Kritis Tanah Sareal Kota Bogor. *Jurnal Teknik Geologi : Jurnal Ilmu Pengetahuan Dan Teknologi*, *8*(1), 47. https://doi.org/10.30872/jtgeo.v8i1.20882

Pamungkas, S. H. R., Yogaswara, L. M., Adhitia, I., & Karmadi, M. A. (2023). Review dan pemetaan lahan kritis dalam wilayah urban. *Jurnal Teknik*, *24*(2), 21–30. https://doi.org/10.33751/teknik.v24i02.9396

Pati, P. K., Kaushik, P., Khan, M. L., & Khare, P. K. (2022). Allometric equations for biomass and carbon stock estimation of small diameter woody species from tropical dry deciduous forests : Support to REDD+. *Trees, Forests and People*, *9*(January), 100289. https://doi.org/10.1016/j.tfp.2022.100289

Rajagukguk, J. R. (2025). Degradasi Lahan dan Ketahanan Pangan. *Jurnal Ilmiah Teknik Dan Sains*, *3*(1), 188–195. https://doi.org/10.62278/jits.v3i1.61

Ramadhan, F. R., Andawayanti, U., & Prasetyorini, L. (2024). Analisis Laju Erosi dan Arahan Penggunaan Lahan Berdasarkan RLKT pada DAS Bedadung Hulu Kabupaten Jember. *Jurnal Teknologi Dan Rekayasa Sumber Daya Air*, *4*(02), 1175–1187. https://doi.org/10.21776/ub.jtresda.2024.004.02.123

Santos, M. J., Smith, A. B., Dekker, S. C., Eppinga, M. B., Leita˜o, P. J., Moreno-Mateos, D., Moreno-mateos, N., & Ruggeri, M. (2021). The role of land use and land cover change in climate change vulnerability assessments of biodiversity : a systematic review. *Landscape Ecol*, *36*, 3367–3382. https://doi.org/10.1007/s10980-021-01276-w

Saputra, Syarif, M., & Achnopha, Y. (2020). Kajian Pendugaan Cadangan Karbon Bawah Permukaan Pada Lahan Bekas Terbakar Di Areal Hutan Lindung Gambut Londerang Kabupaten Tanjab Timur. *Jurnal Agroecotania : Publikasi Nasional Ilmu Budidaya Pertanian*, 2(2), 43–54. https://doi.org/10.22437/agroecotania.v2i2.8740

Shafira, W., Akbar, A. A., & Saziati, O. (2021). Penggunaan Cocopeat Sebagai Pengganti Topsoil Dalam Upaya Perbaikan Kualitas Lingkungan di Lahan Pascatambang di Desa Toba, Kabupaten Sanggau. *Jurnal Ilmu Lingkungan*, *19*(2), 432–443. https://doi.org/10.14710/jil.19.2.432-443

Sugiyono. (2018). *Metode Penelitian Kuantitatif dan Kualitatif dan R&G*. Alfabeta.

Suparwata, D. O. (2017). Pengelolaan Rehabilitasi Lahan Kritis berdasarkan Partisipasi Masyarakat di DAS Randangan Kabupaten Pohuwato Critical Land

Rehabilitation Management Based on Community Participation in Randangan Watershed, Pohuwato District. In *Prosiding Seminar Nasional Lahan Suboptimal* (pp. 978-979). https://doi.org/10.31227/osf.io/uszmh

Suwardji, S., Tejowulan, S., Idrus, A. Al, Syukur, A., Raksun, A., & Parman, P. (2021). Pemberdayaan Masyarakat dalam Rehabilitasi Hutan dan Lahan Kritis Di Wilayah Sekaroh Lombok Timur: Belajar dari Pengalaman Masyarakat. *Jurnal Pengabdian Magister Pendidikan IPA*, *4*(4). https://doi.org/10.29303/jpmpi.v4i4.950

Ulumuddin, Y. I. (2019). Metana: Emisi Gas Rumah Kaca dari Ekosistem Karbon Biru, Mangrove. *Jurnal Ilmu Lingkungan*, *17*(2), 359. https://doi.org/10.14710/jil.17.2.359-372

Wentasari, R., & Lisa, I. (2024). Teknologi Reduksi Emisi Gas Rumah Kacapada Budidaya Padi Sawah Indonesia. *Jurnal Agroqua: Media Informasi Agronomi Dan Budidaya Perairan*, *22*(1), 1–9. https://doi.org/10.32663/ja.v22i1.4190

Yulianingrum, H., Susilawati, H. L., & Pramono, A. (2019). Penerapan Paket Teknologi Ramah Lingkungan Untuk Mengurangi Emisi Metana (CH4) Di Lahan Sawah. *Jurnal Ilmu Lingkungan*, *17*(1), 149. https://doi.org/10.14710/jil.17.1.149-157