

Evaluation of Protected Areas in Bunaken Sub-District, Manado City

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ABSTRACT

This study evaluates the ecological effectiveness of the protected areas in Bunaken mainland sub-district, Manado City, an area that hosts strategically significant ecological assets, including the Tanjung Pisok mangrove protection forest, extensive mangrove ecosystems, and land bordering the Bunaken Marine National Park, while also being directed under the Manado City Spatial Plan (RTRW) 2023–2042 as a priority tourism development zone. The evaluation was carried out through an integrated quantitative spatial-analysis approach combining multitemporal Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 imagery for 2015, 2020, and 2025; biophysical Land Capability Value (Nilai Kemampuan Lahan/NKL) scoring based on slope, soil-erosion sensitivity, and annual average daily rainfall intensity; and a three-part conformance–performance–impact evaluation framework grounded in the Pressure-State-Response model (OECD, 1993), the planning-evaluation theories of Faludi (2000), Alexander (2006), and Talen (1996), and the edge-effect principle in landscape ecology (Forman & Godron, 1986; Murcia, 1995). To eliminate category ambiguity, NKL is operationally defined in this study as Cultivation (Budidaya, NKL <125), Limited Cultivation/Buffer (Budidaya Terbatas, NKL 126–175), and Protected (Kawasan Lindung, NKL >175). Results show that vegetation change across 2015–2025 was spatially selective rather than uniformly degrading, with high-density vegetation cover declining by 29.67 ha at the broader protected-area scale, while the 992.89-ha core study area instead recorded a net increase of roughly 10.6 ha, a divergence concentrated along edge zones bordering settlements and road networks, consistent with edge-effect theory. A class-level land-cover comparison between 2015 and 2025 identified 231.02 ha (23.3% of the study area) of gross land-cover transition, dominated by change in the Mangrove class (107.53 ha, 46.5% of all transition) and Tegalan/Ladang dryland-farming conversion (42.80 ha, 18.5%); the magnitude of the mangrove component is treated as indicative pending field verification (see Limitations). The conformance evaluation, obtained by overlaying 2025 NDVI, biophysical NKL, and RTRW spatial-pattern zoning, identified a conformance gap of 150.31 ha of land that is biophysically and vegetatively suitable for protection yet remains administratively zoned as cultivation land. The performance evaluation, based on the 2015–2020–2025 NDVI trend, indicated that RTRW implementation has been effective across most of the protected area but has weakened along its edges under direct development pressure. The impact evaluation, generated by overlaying NDVI change (Δ NDVI) with NKL change (Δ NKL), produced six impact categories dominated by the Stable class (561.1 ha, 56.49%) and the Moderate class (332.6 ha, 33.49%), while also detecting two small but critical categories: a Hidden-Impact zone of 0.9 ha (0.09%), where vegetation appears to be improving even as biophysical land capacity is declining, partly attributable to inter-annual rainfall variability entering the NKL score (see Section 4.3 and Limitations), and a Very-High Impact zone of 1.2 ha (0.12%), representing simultaneous degradation of both indicators. Collectively, the three evaluation domains converge on a single conclusion: the central issue facing the Bunaken protected area is not large-scale vegetation loss but a structural mismatch between administrative zoning and actual ecological capacity, a segment of which remains ecologically undetected by single-indicator evaluation. These findings provide a spatially explicit, quantitative basis for delineating core and limited-use conservation zones and are recommended as technical input for the preparation of a Bunaken-specific Regional Detailed Spatial Plan (RDTR) and the next revision of the Manado City Spatial Plan.

Keywords: Protected Area, Multitemporal NDVI, Land Capability Value, Conformance-Performance-Impact Evaluation, Edge Effect, Manado City Spatial Plan

INTRODUCTION

Protected areas are a critical component of spatial planning systems because they maintain ecological balance, sustain environmental carrying capacity, and control degradation caused by pressure on land use. The effectiveness of a protected area cannot be assessed from its zoning status in the Spatial Plan (RTRW) alone; it must be evaluated against actual biophysical conditions in both space and time. Protection of these areas is mandated by Law No. 26 of 2007 on Spatial Planning, and reinforced by Government Regulation No. 21 of 2021 and No. 23 of 2021, which affirm that protective function is determined by biophysical condition, vegetation cover, and the intensity of human pressure.

Bunaken mainland sub-district in Manado City hosts strategic ecological assets designated by the Manado City RTRW 2023–2042 as a City Strategic Area for Environmental Carrying Capacity, comprising the Tanjung Pisok mangrove protection forest (14.15 ha), mangrove ecosystems (139.58 ha), and mainland areas bordering the Bunaken Marine National Park and the Tumpa Mountain Forest Park (Tahura). Based on the 2014 and 2023–2042 RTRW documents, the proportion of protected area in Bunaken sub-district increased from approximately 30% to 33%.

Yet the RTRW itself lists programs for "controlling non-conforming spatial utilization" and "consolidating core and utilization zones" for the Marine National Park and Tahura, an administrative acknowledgment that deviations in spatial use and unresolved conservation-zone boundaries have already occurred. This gap is further reflected in the significant discrepancy between the existing mangrove area (139.58 ha) and the city-scale RTRW allocation for "Mangrove Coastal Forest" (17.57 ha), indicating a divide between the planning database and actual field conditions.

Rather than assuming that the Bunaken protected area has already suffered massive damage, this study is grounded in the premise that the area holds a regulatively recognized strategic ecological function while simultaneously being directed as a priority tourism-development zone, without a spatial-quantitative evidence base describing its actual ecological condition. Theoretically, this gap is explained by the edge-effect principle in landscape ecology (Forman & Godron, 1986; Murcia, 1995): the administrative boundary between protected and cultivated land is not an impermeable ecological boundary, allowing pressure from surrounding cultivated land to propagate toward the edge of the protected area without requiring any formal land-use conversion within it.

Existing evaluations of protected areas in Manado City have generally focused on administrative conformance of spatial utilization to the RTRW. Studies that specifically evaluate vegetation dynamics using multitemporal remote sensing, combined with biophysical land-capability assessment and a conformance-performance-impact evaluation framework, have not been found in Manado City's planning literature.

This study addresses that gap by integrating three evaluation dimensions: (1) multitemporal NDVI-based vegetation-dynamics analysis for 2015, 2020, and 2025; (2) biophysical land-capability assessment based on the Land Capability Value (NKL), referring to Ministry of Agriculture Decree No. 837/Kpts/Um/11/1980; and (3) conformance, performance, and impact evaluation based on the Pressure-State-Response framework (OECD, 1993) and conformance-performance evaluation theory (Faludi, 2000; Alexander, 2006; Talen, 1996).

Accordingly, the objectives of this study are: (1) to identify the spatial pattern of vegetation-density condition and change in the protected area during 2015–2025; (2) to analyze the spatial association between land-cover change and vegetation change; and (3) to evaluate the conformance, performance, and impact of the protected area's condition against the spatial-pattern direction of the Manado City RTRW 2023–2042. of the protected area's condition against the spatial-pattern direction of the Manado City RTRW 2023–2042.

LITERATURE REVIEW

The Concept of Protected Areas and Their Ecological Function

A protected area is defined as territory designated with the primary function of preserving environmental sustainability, covering natural, human, and man-made resources (Law No. 26 of 2007). This definition affirms that a protected area is not merely an administrative category within spatial-planning documents but a functional unit that must genuinely perform its ecological role on the ground. Government Regulation No. 23 of 2021 reinforces this by stating that protection forests function as life-support systems, regulating hydrology, preventing flooding, controlling erosion, and maintaining soil fertility. Two dimensions must therefore be satisfied simultaneously for a protected area to be considered effective: a legal-administrative dimension (zoning status in the RTRW) and a biophysical-ecological dimension (actual vegetation condition and land capacity). This study is specifically designed to bridge these two dimensions, which are frequently evaluated separately in Indonesian planning practice.

The Pressure-State-Response (PSR) Framework

The Pressure-State-Response (PSR) framework developed by the Organisation for Economic Co-operation and Development (OECD, 1993) is a three-stage causal analytical model widely used in environmental evaluation for its structural simplicity and its capacity to link cause and effect explicitly. Its three components are defined as follows: Pressure refers to human activity with the potential to alter environmental conditions, such as settlement growth, cultivated-land expansion, or tourism-infrastructure development. State refers to the resulting environmental condition produced by the accumulation of that pressure, represented in this study by two measurable indicators: vegetation density (NDVI) and biophysical land capacity (NKL). Response refers to the policy or institutional instrument formulated to manage pressure and keep environmental conditions within a desired threshold, represented here by the spatial-pattern direction of the Manado City RTRW 2023–2042. The strength of the PSR framework lies in its capacity to transform the evaluative question from "is this area damaged?" into a more precise one: "what pressure is at work, what condition does it produce, and is the existing policy response commensurate with that condition?" This is what distinguishes the present study from conventional protected-area assessments, which generally stop at administrative evaluation alone.

The Edge-Effect Principle as a Pressure-State Transmission Mechanism

A fundamental question left unanswered by the PSR framework is mechanistic: through what pathway can spatial-use pressure outside a protected area alter vegetation conditions within it, without any formal land-use conversion occurring? The answer lies in the edge-effect principle of landscape ecology. Forman and Godron (1986) explain that a landscape is composed of patches, corridors, and a matrix, and that the edge zones bounding these elements possess microclimatic, vegetation-structural, and disturbance characteristics distinct from the core area.

Murcia (1995) further clarifies the mechanism: edge zones experience three types of effects, abiotic effects (changes in light, temperature, and humidity due to exposure to surrounding areas), direct biotic effects (changes in species abundance and distribution due to altered physical conditions), and indirect biotic effects (changes in interspecies interactions such as predation or competition).

In a protected area directly bordering settlements and road networks, as is the case in Bunaken sub-district, this principle carries an important methodological implication: the administrative boundary of a protected area shown on an RTRW map is not an impermeable ecological boundary. External pressure can "seep" into the protected area through informal pathways, surface-temperature increases, disturbance at the vegetation edge, and informal human activity, without ever being recorded as a change in land status within the spatial-planning database. This principle is the theoretical basis for why this study specifically traces the spatial pattern of vegetation change at the area's edge, rather than only aggregating total change across the area.

Spatial-Plan Evaluation: Conformance, Performance, and Impact

Evaluation in planning is a systematic process for assessing the extent to which an established plan achieves its intended objectives (Faludi, 2000). Planning literature distinguishes spatial-plan evaluation into three complementary, rather than substitutive, domains. Conformance evaluation, according to Faludi (2000), assesses the match between existing field conditions and the formally adopted plan; in this study it is operationalized through a three-layer spatial overlay of actual vegetation condition (2025 NDVI), biophysical land capacity (NKL), and the RTRW 2023–2042 spatial-pattern direction. Performance evaluation, as emphasized by Alexander (2006) and Talen (1996), addresses a key limitation of conformance evaluation: Talen (1996) proposes that plan-implementation success be assessed from the trend of condition change over time rather than a single snapshot; this study therefore complements conformance evaluation with a multitemporal NDVI trend analysis for 2015–2020–2025, assessing whether the RTRW's effectiveness in maintaining protective function has been consistent or has weakened during particular periods. Impact evaluation, as Talen (1996) further argues, addresses a blind spot that persists even when conformance and performance are combined: both typically assess a single condition indicator (in this case, surface vegetation) independently of the underlying structural land capacity that sustains it. This study operationalizes impact evaluation by simultaneously overlaying NDVI change (ΔNDVI) with NKL change (ΔNKL), enabling detection of what is termed hidden impact, areas where vegetation appears to be improving while the biophysical capacity of the land is in fact declining.

The Normalized Difference Vegetation Index (NDVI) as a Vegetation-Condition Indicator

The Normalized Difference Vegetation Index (NDVI) is a remote-sensing-based vegetation index that measures greenness and vegetation density from spectral response to electromagnetic radiation. Tucker (1979) explains that healthy vegetation intensively absorbs red-band radiation for photosynthesis while strongly reflecting near-infrared (NIR) radiation owing to leaf cellular structure; the difference in reflectance between these two bands forms the basis of the NDVI calculation. NDVI values range from -1 to $+1$, where values approaching $+1$ indicate dense, healthy vegetation, values near 0 indicate sparse vegetation or non-vegetated land, and negative values generally represent non-vegetated objects such as water bodies or clouds. This study classifies vegetation density into three classes referring to Ministry of Forestry Regulation No. P.12/Menhut-II/2012:

Table 1. NDVI Classification

No	NDVI Classification	NDVI Value
1	Low	-1,00 s.d 0,32
2	Moderate	0,32 s.d 0,42
3	High	0,42 s.d 1,00

Source : Permenhut RI Nomor P.12/Menhut-II/2012

Low (-1.00 to 0.32), Moderate (0.32 to 0.42), and High (0.42 to 1.00). NDVI was chosen as the primary vegetation-condition indicator because it is objective, quantitative, and consistently measurable across

different time periods (multitemporal), a characteristic essential for the performance evaluation, which requires trend data rather than a single snapshot.

Land Capability Value (NKL) as an Indicator of Biophysical Capacity

Whereas NDVI represents the condition of surface vegetation, the Land Capability Value (Nilai Kemampuan Lahan/NKL) represents the structural land capacity that sustains that vegetation. This concept is rooted in the land-suitability framework developed by the Food and Agriculture Organization (FAO, 1976), which defines land suitability as the degree of fitness of a given land unit for a particular use based on its overall biophysical characteristics, rather than its land-cover condition at a single point in time. In this study, NKL is calculated based on Ministry of Agriculture Decree No. 837/Kpts/Um/11/1980, which establishes three biophysical parameters: slope gradient (maximum score of 100), soil type based on erosion sensitivity (maximum score of 75), and average daily rainfall intensity (maximum score of 50), yielding a maximum total NKL score of 225. To eliminate any ambiguity in category naming, this study operationally defines the three resulting land-capacity categories as follows: Cultivation Area (Kawasan Budidaya) for NKL <125; Limited Cultivation/Buffer Area (Kawasan Budidaya Terbatas) for NKL 126–175; and Protected Area (Kawasan Lindung), biophysically obligated to serve a protective function, for NKL >175. This threshold interpretation is applied consistently throughout Section 4, and all subsequent category labels (Cultivation/Buffer/Protected) refer directly to these numerical NKL ranges as defined here, rather than to any independent classification. Presidential Decree No. 32 of 1990 reinforces this criterion by establishing that land with a slope of $\geq 40\%$ is absolutely required to be designated as protected area, irrespective of other parameters.

Table 2. NKL Instrument: Biophysical Scoring of Protected Areas (SK Mentan 837/1980)

No	Indicator	Measurement Parameter	Class / Criteria	Score (Si)	Regulatory Basis
1	Slope Gradient	Percentage (%) from DEM SRTM/DEMNAS	> 40%	100	SK Mentan 837/1980; Presidential Decree 32/1990: slope $\geq 40\%$ mandatorily protected; Government Regulation 23/2021
			25 – 40%	80	
			15 – 25%	60	
			8 – 15%	40	
			0 – 8%	20	
2	Soil Type (Erosion Sensitivity)	Erodibility classification; Thematic soil data, Manado RTRW	Regosol, Litosol, Organosol, Renzina (extremely sensitive)	75	SK Mentan 837/1980; FAO (1976): soil erodibility as a determinant of protected-area biophysical sensitivity
			Andosol, Laterite, Grumosol, Podsol, Podzolic (sensitive)	60	
			Brown Forest, Non-calci Brown, Mediterranean (moderately sensitive)	45	
			Latosol (less sensitive)	30	

			Alluvial, Gley, 15 Planosol, Hydromorphic, Laterite (not sensitive)		
3	Average Daily Rainfall Intensity	mm/day; BMKG / BPS Manado, Manado average annual rainfall	> 34.8 mm/day (very high)	50	SK Mentan 837/1980; Government Regulation 23/2021: hydrological function of protected areas
			27.7 – 34.8 mm/day (high)	40	
			20.7 – 27.7 mm/day (moderate)	30	
			13.6 – 20.7 mm/day (low)	20	
			< 13.6 mm/day (very low)	10	

NKL Classification	Area Status	Remarks
≥ 175	Protected Area	Biophysically fit and mandatorily required to serve a protective function (SK Mentan 837/1980)
125 – 174	Limited Cultivation Area	Transition zone; requires further assessment and strict control
< 125	Cultivation Area	Does not meet the biophysical criteria for a protected area

Source: Decree of the Minister of Agriculture No. 837/Kpts/Um/11/1980; Presidential Decree No. 32 of 1990; FAO (1976); Government Regulation No. 23 of 2021

Because the three parameters that constitute NKL (slope, soil type, and long-term average rainfall) are relatively static over a decadal timescale, NKL functions as a baseline of land capacity that is independent of seasonal or annual vegetation fluctuation. It is precisely this combination of NDVI (dynamic, representing surface condition) and NKL (relatively static, representing structural capacity) that allows this study to detect hidden-impact conditions that cannot be captured by vegetation evaluation alone.

RESEARCH METHODS

This study employs a quantitative approach based on spatial analysis, using an evaluative-descriptive method.

Research Location

The research covers the protected area within five urban villages (kelurahan) of Bunaken sub-district (Molas, Tongkaina, Meras, Bailang, and Pandu), Manado City, encompassing a study area of approximately 992.89 ha out of the sub-district's total protected area of 1,002.5 ha.

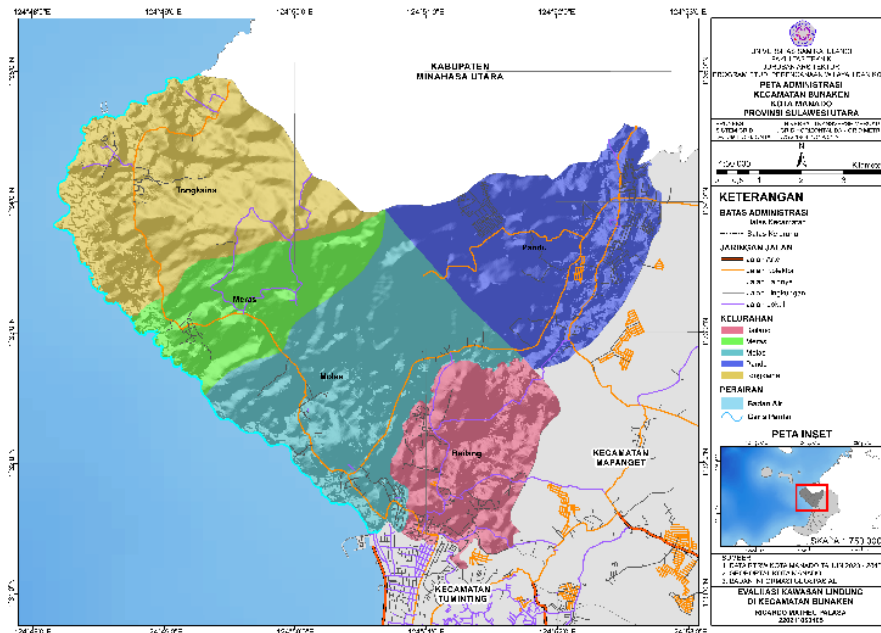


Figure 1. Administrative and Protected-Area Boundary Map of Bunaken Sub-district

Source: RTRW Manado City 2023–2042; BPS Manado City, 2022 (processed, 2026)

Data and Materials

Primary data consist of Sentinel-2 Level-2A imagery (ESA Copernicus) for 2015, 2020, and 2025, acquired during the dry season (May–September) to minimize seasonal variation. Secondary data include the SRTM/DEMNAS Digital Elevation Model, BPN/BBSDLP soil maps, BMKG rainfall records, and the Manado City RTRW 2023–2042 spatial-pattern map. Slope and soil-type layers used in the NKL computation were held constant across both analysis years, consistent with their physically static nature.

Rainfall-intensity data, by contrast, were derived from BMKG station records converted into the average daily rainfall specific to each respective analysis year (2015 and 2025) rather than a multi-year climatological baseline; the methodological implications of this choice for the temporal stability of the NKL indicator are examined in Section 4.3 and acknowledged in the Limitations.

Data Analysis Technique

Analysis was conducted in four stages. First, multitemporal NDVI analysis for 2015, 2020, and 2025 through atmospheric correction and three-class vegetation-density classification. Second, land-cover classification for 2015 and 2025 was performed independently for each year using the same class scheme (Danau/Lake, Mangrove, Hutan/Forest, Kebun Campuran/Mixed Garden, Permukiman/Settlement, Rawa/Swamp, Semak Belukar/Shrubland, Sungai/River, Tambak/Fishpond, Tanah Terbuka/Bare Land, Tegal-Ladang/Dryland Farming, and RTH/Green Open Space), from which a class-level land-cover change map was derived by direct spatial comparison (post-classification change detection) of the two independently classified years; this LULC change layer was then spatially associated with NDVI change (ΔNDVI) through overlay.

Third, conformance evaluation was conducted through a three-layer overlay ($2025 \text{ NDVI} \times \text{NKL} \times \text{RTRW}$ spatial pattern) producing a conformance matrix. Fourth, performance evaluation was conducted through reclassification of land cover into vegetated/non-vegetated status to assess the consistency of protective-direction implementation from 2015 to 2025, together with impact evaluation through an overlay of $\Delta\text{NDVI} \times \Delta\text{NKL}$ on the common spatial footprint of 2015–2025 (to avoid bias from any residual edge-of-raster or

coastline-masking differences between years), producing six impact-level categories: Stable, Very Low, Low, Moderate, Hidden High (hidden impact), and Very High.

Classification Reliability and Accuracy Assessment

A limitation common to many retrospective remote-sensing studies is the unavailability of the original classification raster and field-based training/validation samples once the mapping stage is complete; in this study, the raw classification files were not retained beyond the production of the final land-cover maps, and no field survey was conducted at the time of classification. Consequently, a formal pixel-based accuracy assessment (confusion matrix and Kappa coefficient) following Congalton (1991) could not be computed for this manuscript. As a partial, non-substitutive mitigation, the resulting land-cover boundaries for both 2015 and 2025 were qualitatively cross-checked against two independent reference sources, BPS Manado City land-use statistics (2022) and the Manado City RTRW 2023–2042 spatial-pattern map, and were found to be broadly consistent in the overall distribution and extent of forest, settlement, and cultivated land.

This qualitative cross-check increases confidence in the general spatial pattern reported but does not constitute a statistically valid accuracy assessment, and the reported land-cover areas should therefore be interpreted as indicative rather than accuracy-certified. This constraint, its implications for specific findings (particularly the magnitude of mangrove-class change reported in Section 4.2), and the recommended remedy for future work are discussed further in the Limitations section.

RESULTS AND DISCUSSION

Vegetation-Density (NDVI) Dynamics, 2015–2025

Multitemporal NDVI analysis shows that high-density vegetation dominated the study area throughout the observation period (Table 1). At the protected-area scale, high-density vegetation cover declined from 3,042.51 ha (95.0%) in 2015 to 3,012.84 ha (94.0%) in 2025, a net decrease of 29.67 ha over the decade.

At the study-area scale, by contrast, the trend actually increased from 985.1 ha (98.26%) to 995.7 ha (99.32%). This divergence is spatially selective and concentrated at edge zones bordering settlements and road networks, consistent with the edge-effect principle (Forman & Godron, 1986).

Table 3. High-Density Vegetation Dynamics in the Protected Area, 2015–2025

Year	Protected Area (ha)	%	Study Area (ha)	%
2015	3,042.5	95.0	985.1	98.3
2020	3,027.9	94.5	994.3	99.2
2025	3,012.8	94.0	995.7	99.3
Total Area	3,203.3	100.0	1,002.5	100.0

Source: Multitemporal Sentinel-2 NDVI Analysis, 2026

Association between Land-Cover Change and Vegetation Change

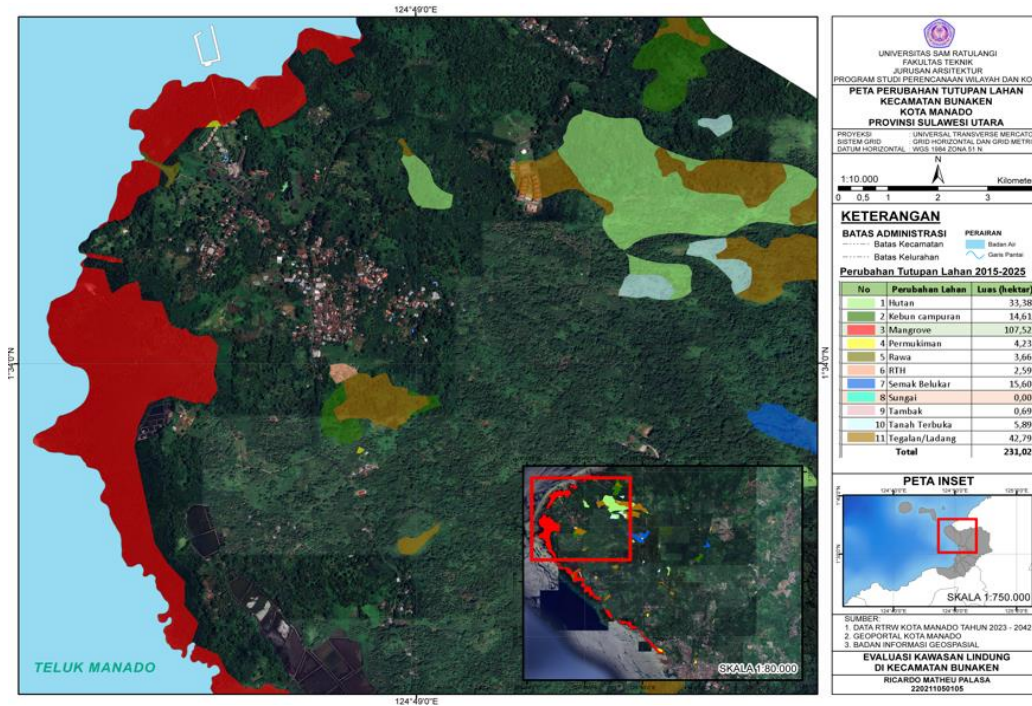


Figure 2. Land-Cover Change Map, Bunaken Sub-District, 2015–2025

Source: RTRW Manado City 2023–2042; Geoportal Kota Manado; Badan Informasi Geospasial (processed, 2026)

Table 4. Gross Land-Cover Change by Class, Bunaken Protected Area, 2015–2025

Land-Cover Class	Changed Area (ha)	% of Total Change
Mangrove	107.527	46.54
Tegalan/Ladang (Dryland Farming)	42.795	18.52
Hutan (Forest)	33.382	14.45
Semak Belukar (Shrubland)	15.600	6.75
Kebun Campuran (Mixed Garden)	14.617	6.33
Tanah Terbuka (Bare Land)	5.898	2.55
Permukiman (Settlement)	4.239	1.83
Rawa (Swamp)	3.667	1.59
RTH (Green Open Space)	2.599	1.13
Tambak (Fishpond)	0.692	0.30
Sungai (River)	0.004	0.00

Source: Post-Classification Land-Cover Change Detection, Sentinel-2 2015–2025 (processed, 2026)

A class-level land-cover change map was produced by comparing the independently classified 2015 and 2025 land-cover layers (Figure 2). Across the 992.89-ha study area, a gross total of 231.02 ha (23.3% of the study area) underwent a class-level land-cover transition between 2015 and 2025 (Table 2). This gross transition figure is conceptually distinct from, and considerably larger than, the net vegetation-density change captured by the NDVI analysis in Section 4.1, because it captures every class-to-class reclassification detected between the two dates, including transitions among non-forest classes, rather than only measurable declines or increases in vegetation greenness.

The largest single component of this change is the Mangrove class (107.53 ha, 46.5% of total transitioned area), followed by Tegalan/Ladang dryland-farming conversion (42.80 ha, 18.5%) and the Hutan/Forest class (33.38 ha, 14.5%). Semak Belukar (shrubland, 15.60 ha, 6.8%) and Kebun Campuran (mixed garden, 14.62 ha, 6.3%) account for a further substantial share, while Tanah Terbuka (bare land), Permukiman (settlement), Rawa (swamp), RTH (green open space), Tambak (fishpond), and Sungai (river) together contribute the remaining 6.3 ha (2.7%).

The magnitude of the mangrove-class transition warrants particular caution in interpretation. Ecologically mature mangrove stands do not typically establish at a scale of over 100 ha within a single decade; the reported figure more plausibly reflects a combination of genuine mangrove expansion at the seaward fringe (recruitment into previously bare or sparsely vegetated intertidal flats) and spectral confusion with adjacent forest and shrub classes at Sentinel-2's 10 m spatial resolution. This study therefore treats the reported mangrove-class change as indicative of a real expansion trend rather than a precisely quantified figure, and recommends targeted field verification before the 107.53 ha figure is used for regulatory or planning purposes (see Limitations). Beyond the mangrove component, the concentration of change in mixed and marginal classes: Tegalan/Ladang, Semak Belukar, and Kebun Campuran, rather than in the core Hutan class, supports the broader conclusion that ecological pressure on the Bunaken protected area is incremental and edge-concentrated rather than indicative of large-scale core-habitat deforestation, consistent with the edge-effect principle (Forman & Godron, 1986).

Biophysical Land Capability Value (NKL)

Table 5. Land Capability Value (NKL) Category Areas, 2015 vs. 2025

NKL Category	2015 (ha)	2015 (%)	2025 (ha)	2025 (%)
Cultivation (Budidaya, NKL <125)	193.6	19.59	153.3	15.43
Buffer (Budidaya Terbatas, NKL 126–175)	427.2	43.22	754.9	75.99
Protected (Kawasan Lindung, NKL >175)	367.6	37.19	85.3	8.59
Total Scored NKL Area	988.4	100.00	993.5	100.00

Source: NKL Scoring based on SK Mentan 837/Kpts/Um/11/1980; BMKG Manado City rainfall records, 2026 (processed, 2026)

NKL scoring was computed independently for 2015 and 2025 following the operational thresholds defined in Section 2.6 (Cultivation: NKL <125; Buffer: NKL 126–175; Protected: NKL >175). The results (Table 3) show a substantial decline in the Protected category, from 367.6 ha (37.19% of total scored area) in 2015 to 85.3 ha (8.59%) in 2025, alongside an increase in the Buffer category from 427.2 ha (43.22%) to 754.9 ha (75.99%) and a smaller decline in the Cultivation category from 193.6 ha (19.59%) to 153.3 ha (15.43%).

Because slope gradient and soil-erosion sensitivity are physically static parameters at the decadal scale, and were held constant across both analysis years in this study (Section 3.2), this magnitude of category shift cannot be attributed to genuine topographic or pedological change. The most plausible driver is instead the rainfall-intensity component of the NKL score, which was derived from BMKG records converted into the average daily rainfall specific to each analysis year rather than a multi-year climatological baseline (Section 3.2). Inter-annual rainfall variability between 2015 and 2025, for instance, differing El Niño–La Niña conditions, can meaningfully shift the rainfall-intensity score component even while slope and soil parameters remain entirely unchanged. This represents an important methodological caveat: although NKL is conceptually intended as a temporally static biophysical baseline, its rainfall component as operationalized in this study introduces genuine temporal sensitivity, and the reported Δ NKL should be interpreted as partly reflecting inter-annual climatic variability rather than solely a permanent change in land capacity. This limitation, and the recommended remedy (use of a multi-year climatological rainfall average), is discussed further in the Limitations section.

The residual discrepancy between the total scored NKL area and the fixed study locus (1,002.5 ha in both years), 14.1 ha in 2015 and 9.0 ha in 2025, corresponds to unscored water-body pixels (rivers, ponds, and standing water) that fall outside the slope–soil–rainfall raster coverage used for NKL computation; because the mapped extent of water bodies differs marginally between the 2015 and 2025 land-cover classifications, this unscored area also differs marginally between years. This discrepancy is unrelated to any change in the administrative boundary of the study locus, which remained fixed at 1,002.5 ha throughout the analysis.

Conformance Evaluation

A three-layer overlay (2025 NDVI $\times$ NKL $\times$ RTRW spatial pattern) applied to the 992.89-ha study area yields the following distribution: the Fairly Suitable category dominates with 752.71 ha (75.81%), followed by the Needs Evaluation–Potential Protected category at 150.31 ha (15.14%), the Suitable category at 85.30 ha (8.59%), and the Unsuitable/Low-Density category at 4.57 ha (0.46%). The most substantive finding is the identification of 150.31 ha of land that is biophysically and vegetatively fit to serve a protective function yet remains regulatively zoned as cultivation land in the RTRW, a conformance gap that confirms the data gap identified in the Introduction.

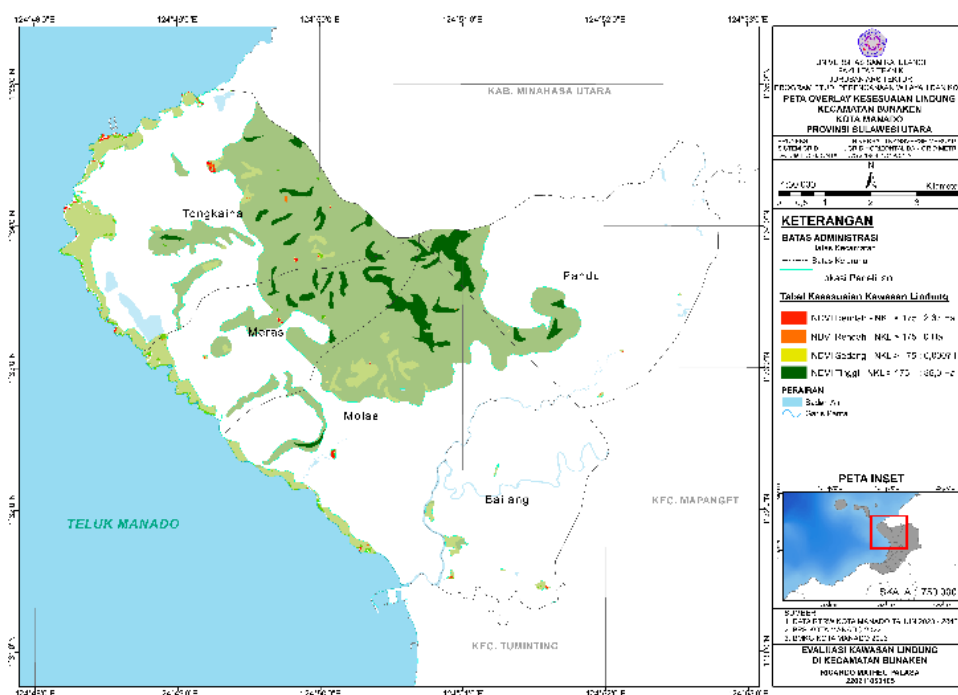


Figure 3. Conformance Evaluation Map of the Bunaken Sub-district Protected Area, 2015–2025

Source: NDVI & NKL Overlay Analysis; RTRW Manado City 2023–2042; BPS Manado City 2022; BMKG Manado City 2026 (processed, 2026)

Table 6. Conformance of the Protected Area with the RTRW 2023–2042

Category	Area (ha)	%
Suitable	85.30	8.51
Fairly Suitable	752.71	75.08
Needs Evaluation	150.31	14.99
Unsuitable	14.18	1.41
Total	1,002.50	100.00

Source: NDVI, NKL, and RTRW Overlay Analysis, 2026

Performance Evaluation

Performance evaluation assesses the effectiveness of RTRW implementation from the multitemporal NDVI trend (Table 1). The stagnant-to-declining trend at the protected-area scale, contrasted with the improving trend within the study area, indicates that RTRW implementation performance in sustaining protective function is not spatially uniform: relatively effective across most of the area, yet weakening at edge zones directly bordering development pressure, in line with the principle that plan performance should be assessed from trends of change rather than a single-point condition (Talen, 1996).

Impact Evaluation

Overlaying $\Delta\text{NDVI} \times \Delta\text{NKL}$ for 2015–2025 on the common spatial footprint produces six impact categories. The Stable category dominates with 561.1 ha (56.49%), followed by Moderate at 332.6 ha (33.49%), Low at 96.8 ha (9.75%), and Very Low at 0.6 ha (0.06%). The most substantive finding lies in the two smallest yet most consequential categories: the Hidden-Impact category, covering 0.9 ha (0.09%), representing areas where vegetation appears to be improving while biophysical capacity is declining, a condition undetectable through vegetation indicators alone, and the Very-High category, covering 1.2 ha (0.12%), representing simultaneous degradation of both indicators.

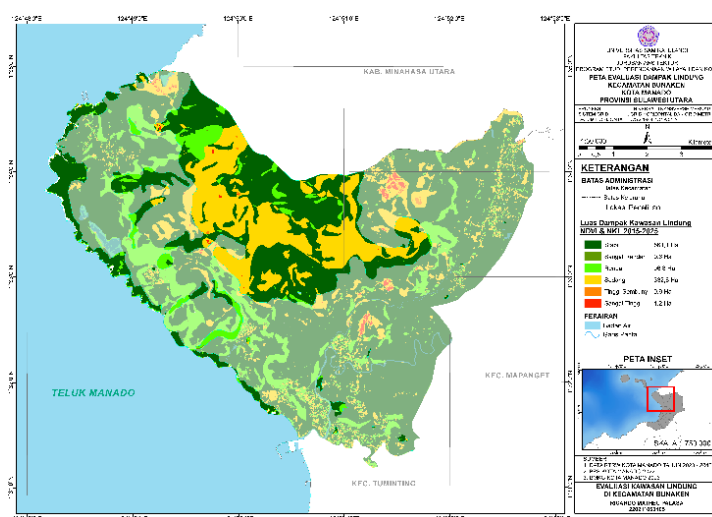


Figure 4. Impact Evaluation Map of the Bunaken Sub-district Protected Area, 2015–2025

Source: NDVI & NKL Overlay Analysis; RTRW Manado City 2023–2042; BPS Manado City 2022; BMKG Manado City 2026 (processed, 2026)

Although the two critical categories together account for only 2.1 ha (0.21%) of the total study area, their spatial presence demonstrates that hidden ecological risk is real, even at a limited scale, and would remain undetected by conformance or performance evaluation alone, each of which assesses a single parameter in isolation.

Synthesis of the Three Evaluation Domains

The three evaluation domains produce coherent and complementary conclusions. The conformance evaluation shows that only 8.59% of the study area is fully consistent between biophysical-vegetative condition and RTRW zoning. The performance evaluation shows a spatially non-uniform implementation trend, effective across most of the area but weakening at its edges. The impact evaluation identifies a hidden ecological-risk zone of 0.9 ha undetected by the other two evaluations. All three converge on a single conclusion: the central issue in the Bunaken sub-district protected area is not massive vegetation loss but a structural gap between administrative zoning and actual ecological capacity, a condition that, if left uncorrected through an RTRW review, risks legitimizing the gradual conversion of land that should be maintained as a life-support system (Government Regulation No. 23 of 2021).

LIMITATIONS

Several methodological limitations of this study should be acknowledged to properly contextualize its findings and to guide future refinement.

First, classification accuracy for the 2015 and 2025 land-cover maps was not formally assessed through a field-based confusion matrix or Kappa coefficient (Congalton, 1991), as the raw classification rasters and any associated training/validation samples were not retained beyond completion of the original mapping process, and no field survey was conducted at the time of classification. As a partial, non-substitutive mitigation, the resulting land-cover boundaries were qualitatively cross-checked against BPS Manado City land-use statistics (2022) and the RTRW 2023–2042 spatial-pattern map, and were found broadly consistent in the overall distribution of forest, settlement, and cultivated land; however, this does not substitute for a statistically valid accuracy assessment, and the reported land-cover areas should be treated as indicative rather than accuracy-certified. Future iterations of this research should incorporate a stratified random sample of independent reference points, interpreted via very-high-resolution historical imagery (e.g., Google Earth Pro) where field access is constrained, or through direct field verification where feasible, to compute Overall Accuracy, Producer's/User's Accuracy, and the Kappa coefficient following standard remote-sensing accuracy-assessment protocols (Congalton, 1991; Olofsson et al., 2014).

Second, the NKL indicator, while conceptually intended as a temporally static biophysical baseline, was operationalized using rainfall-intensity data converted into the average daily rainfall specific to each analysis year rather than a multi-year climatological average (Sections 3.2 and 4.3). This introduces genuine inter-annual climatic variability into an indicator meant to represent stable land capacity, meaning that part of the observed Δ NKL, including the 0.9 ha Hidden-Impact zone reported in Section 4.6, may partly reflect short-term rainfall variation rather than a permanent change in biophysical capacity. Future application of the NKL framework should use a multi-year (e.g., 10–20 year) climatological average rainfall to preserve the temporal stability the indicator is intended to provide.

Third, the magnitude of mangrove-class change identified in the land-cover comparison (107.53 ha, Section 4.2) exceeds what would ecologically be expected from natural mangrove establishment within a single decade, and likely reflects some combination of genuine seaward expansion and spectral/boundary confusion with adjacent classes at Sentinel-2's 10 m spatial resolution. This figure should be treated as indicative of an expansion trend pending field verification, rather than as a precisely validated area.

Fourth, no Regional Detailed Spatial Plan (Rencana Detail Tata Ruang/RDTR) currently exists specifically for Bunaken Sub-District; the only available spatial-pattern reference operating at the sub-district scale is the city-wide Manado RTRW 2023–2042 map. This constrains the precision with which the 150.31 ha

conformance gap identified in this study can currently be operationalized at the parcel level, pending the eventual preparation of a Bunaken-specific RDTR, as discussed in the Recommendations.

CONCLUSION

This study evaluates the effectiveness of the protected areas in Bunaken sub-district through the integration of multitemporal remote-sensing analysis, biophysical land-capacity assessment, and a conformance-performance-impact evaluation framework (Faludi, 2000; Alexander, 2006; Talen, 1996), with the following conclusions.

First, regarding the spatial pattern of vegetation-density condition and change (Objective 1), vegetation change in the Bunaken protected area during 2015–2025 is spatially selective rather than a case of overall degradation: high-density vegetation declined by 29.67 ha at the protected-area scale, yet increased by 10.6 ha within the study area. This divergence is concentrated at edge zones bordering settlements and road networks, consistent with the theoretical prediction of the edge-effect principle (Forman & Godron, 1986; Murcia, 1995).

Second, regarding the spatial association between land-cover change and vegetation change (Objective 2), a class-level land-cover comparison identified 231.02 ha (23.3% of the study area) of gross land-cover transition between 2015 and 2025, dominated by change in the Mangrove class (107.53 ha, 46.5%, treated as indicative pending field verification, see Limitations) and Tegalan/Ladang dryland-farming conversion (42.80 ha, 18.5%), with the remainder distributed across Hutan, Semak Belukar, Kebun Campuran, and other classes. The concentration of change in marginal and mixed classes rather than in core forest demonstrates that the area's ecological change is edge-concentrated and incremental rather than indicative of large-scale core-habitat deforestation.

Third, regarding the conformance, performance, and impact evaluation of the protected area's condition against the RTRW (Objective 3), this study identifies a conformance gap of 150.31 ha of land that is fit for protection yet zoned for cultivation; a performance trend that weakens spatially at the area's edges; and a hidden-impact risk of 0.9 ha undetected by conventional single-indicator evaluation.

These three findings converge to confirm that the fundamental issue facing the Bunaken protected area is not massive vegetation loss but a structural mismatch between administrative zoning and actual ecological condition. The Bunaken sub-district protected area therefore requires the delineation of conservation zoning (core zones and limited-use zones) based on spatial-quantitative data such as that generated by this study, to serve as technical grounds for the next revision of the Manado City RTRW, bridging the gap between the administrative acknowledgment of spatial-utilization issues already recorded in the RTRW and KLHS and the measurable ecological evidence found in the field.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

The Manado City Government is advised to prioritize the 150.31 ha conformance-gap area identified in this study for reclassification toward protective zoning. Because no Bunaken-specific Regional Detailed Spatial Plan (RDTR) currently exists, the only available reference being the city-wide RTRW 2023–2042 spatial-pattern map, two administrative pathways are available. The first is incorporating the reclassification into the next formal revision of the Manado City RTRW (Peraturan Daerah), which requires DPRD approval and is typically undertaken on a multi-year review cycle; since the current RTRW 2023–2042 is only in its early implementation years, this pathway is unlikely to be available in the near term. The second, more immediately actionable pathway is initiating the preparation of a dedicated RDTR for Bunaken Sub-District, accompanied by a Peraturan Zonasi (Zoning Regulation) as mandated under Law No. 26 of 2007 on Spatial Planning and its implementing regulations; an RDTR operates at a finer parcel-level resolution than the city-wide RTRW and can directly incorporate this study's spatial-quantitative conformance findings without waiting for the RTRW's next full revision cycle. Given the current planning timeline, pathway two represents the more

practicable near-term mechanism for translating this study's findings into a binding zoning instrument, and is recommended as the primary policy avenue.

Spatial-planning enforcement should give particular attention to edge zones bordering settlements and road networks, where vegetation performance is shown to weaken, by strengthening buffer-zone management and monitoring of informal land-use pressure.

The 0.9 ha hidden-impact zone identified through the $\Delta\text{NDVI} \times \Delta\text{NKL}$ overlay warrants targeted field verification and closer monitoring, since its risk would remain undetected by conformance or vegetation-only evaluation alone.

Future research is encouraged to extend the analysis with additional biophysical or socio-economic pressure indicators, broaden the multitemporal NDVI time series, and refine the NKL parameter base with more recent soil and rainfall data as they become available.

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