



## RESEARCH ARTICLE

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# Soil Fertility Assessment and Spatio-Temporal Analysis of Paddy Field Change In Gorontalo Under LP2B Policy

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## Abstract

This study quantitatively assessed the intrinsic soil quality and spatio-temporal dynamics of paddy field conversion in Gorontalo Regency between 2017 and 2023, specifically under the Sustainable Food Agricultural Land (LP2B) policy. The fundamental inquiry of this research concerns the real efficacy of passive regulatory policy instruments in protecting agricultural natural capital against intense development pressures. Utilizing Sentinel satellite imagery and the Random Forest algorithm within the Google Earth Engine (GEE), detailed change detection and zonal analyses were performed. This was augmented by empirical field sampling and laboratory analysis to quantify the mean levels of critical soil fertility indicators, including Organic Carbon (OC) and Total Nitrogen (TN), in protected and newly established areas. A significant policy paradox was identified. While the regency experienced a net increase of 4,226.54 ha in total paddy field area, the legally protected LP2B zones suffered an undeniable net loss of 23.76 ha. Crucially, the soils lost from LP2B areas were intrinsically superior, exhibiting significantly higher mean levels of OC (3.15% vs. 1.88%) and TN (0.28% vs. 0.15%) compared to the newly established areas outside the LP2B boundary, which utilized lower-quality, marginal land. The most important findings highlight that the policy has failed to preserve the highest quality land, resulting in resource substitution (quality for quantity). This study strongly recommends the adoption of spatially targeted incentive strategies and the integration of a Weighted Land Loss Metric, based on soil fertility parameters, into policy monitoring to ensure the long-term sustainability and resilience of regional food production systems.

**Keywords:** Gorontalo, LP2B Policy, Paddy Field Change, Remote Sensing, Soil Fertility, Soil Natural Capital

## 1. Introduction

The stability of Indonesia's socio-economy and its national food security are fundamentally reliant on the agricultural sector. However, this sector faces structural threats characterized by continuous and intensive conversion of productive agricultural land (Badan Pusat Statistik 2022). This phenomenon, occurring predominantly in peri-urban areas, is driven by industrial expansion, infrastructure development, and accelerated urban growth (Deng et al. 2008; Pribadi & Pauleit 2015). A direct consequence of this uncontrolled land-use transformation is a demonstrable decline in long-term agricultural productive capacity, directly challenging national food resilience (Liu et al. 2013).

Land conversion does not solely involve the loss of physical area; more crucially, it represents the depletion of non-renewable soil natural capital. When high-quality land

is converted, the resulting productivity loss cannot be easily offset by relocating farming activities to marginal lands, primarily due to fundamental differences in intrinsic soil quality (Lambin & Meyfroidt 2011). Previous research on soil assessment in tropical paddy systems has shown that variations in Organic Carbon (OC), Total Nitrogen (TN), and P-K availability critically determine land productivity and resilience (Aslam & Fazal, 2025; Fitri, Adiwibowo, & Pravitasari, 2022). These key soil fertility parameters represent the actual, physical stock of agricultural resources.

To address this fundamental threat, the Government of Indonesia established the Sustainable Food Agricultural Land (LP2B) policy through Law No. 41 of 2009 (Presiden Republik Indonesia, 2009). This legislation mandates the careful protection of prime agricultural lands, designating specific zones where conversion is legally restricted or

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prohibited. While the objectives of the LP2B policy are conceptually sound, field implementation encounters serious obstacles. Passive regulatory policies often struggle against significantly stronger market economic incentives, leading to persistent land conversion even within supposedly protected zones (Verburg et al., 2015). This contradiction creates a policy paradox where legal boundary setting (*de jure protection*) does not guarantee physical preservation (*de facto preservation*).

Most existing studies on agricultural land vulnerability focus either on broad land change monitoring frameworks or large-scale spatial analyses (Chen et al., 2015). Although these studies provide valuable descriptive insights, they often overlook two crucial dimensions for robust LP2B policy evaluation: the empirical efficacy of the protective boundaries themselves and the intrinsic quality (fertility) of the land being protected or lost. A significant knowledge gap lies in the lack of direct quantitative evaluations that integrate observed land conversion patterns within official policy boundaries with a commensurate assessment of the corresponding loss of soil natural capital. This gap limits the understanding of the *weighted performance* of the LP2B policy within specific regional contexts such as Gorontalo Regency.

Gorontalo Regency (geographically situated at 0°32'–1°05' N; 122°12'–123°45' E) is a primary food production center currently undergoing substantial infrastructure development pressure, with varying elevations (ranging

from 0 up to over 2,000 meters above sea level [masl]). This study directly addresses the aforementioned deficiency. The primary contribution of this research lies in its methodological integration, combining high-precision spatio-temporal analysis of paddy field change (2017–2023) with a critical comparative assessment of soil nutrient content (intrinsic quality) between designated LP2B zones and newly expanding areas. This multi-method approach allows for an evaluation that moves beyond mere area metrics to quantify the real cost of policy failure—the depletion of non-renewable and irreversible natural resources.

Specifically, this study aims to: (1) analyze the spatio-temporal dynamics of paddy field change within and outside the established LP2B zones; and (2) assess the intrinsic soil fertility differences to evaluate the effectiveness of the LP2B policy implementation.

## 2. Material and Methods

This research adopted a retrospective analytical design utilizing a comprehensive multi-method approach, integrating advanced geospatial satellite imagery analysis with field surveys and laboratory soil quality analysis. This design was selected to quantify historical land change patterns over six years (2017–2023) and, critically, to assess the fundamental quality differences between protected agricultural resources (LP2B) and newly developed resources (Non-LP2B).

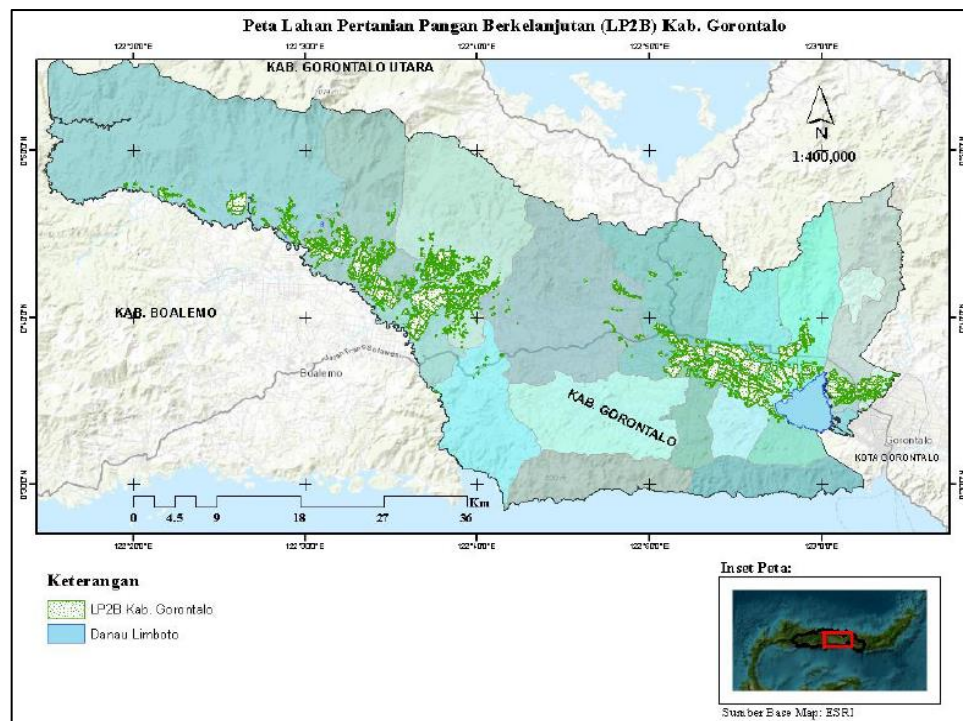


Figure 1. Research Location Map

### 2.1. Study Location and General Procedure

The study was conducted in Gorontalo Regency (Figure 1), Gorontalo Province, Indonesia, characterized by

low-lying to undulating topography (average elevation 50–300 masl) with the central study coordinates approximately 0°41' N and 123°04' E. The geospatial analysis covered the

entire administrative boundary of the regency, while soil sampling focused on sub-districts demonstrating the highest conversion and expansion pressures (Telaga and Boliyohuto).

The research workflow commenced with satellite data acquisition, followed by classification and land change detection analysis using the Google Earth Engine (GEE) platform. The spatial analysis results were then utilized to guide the field soil sampling. Samples were analyzed in the laboratory to determine fertility indicators, and the resulting data were integrated through statistical analysis for policy effectiveness evaluation.

A methodological flowchart was added to provide an integrated picture of the research stages, from Sentinel-2 image collection, processing in Google Earth Engine, Random Forest classification, field validation, to laboratory analysis and spatial interpretation. The flowchart is presented in Figure 2.

## 2.2. Geospatial Data Collection and Pre-processing

Geospatial data were sourced from Sentinel-2 optical imagery and Sentinel-1 Synthetic Aperture Radar (SAR) data. All data processing was conducted using the cloud-based Google Earth Engine (GEE) platform (Gorelick et al., 2017). Administrative boundaries and official LP2B boundaries were obtained from relevant local government agencies. Road network data, used for analyzing infrastructure pressure, were sourced from OpenStreetMap (OSM).

## 2.3. Paddy Field Classification and Change Detection

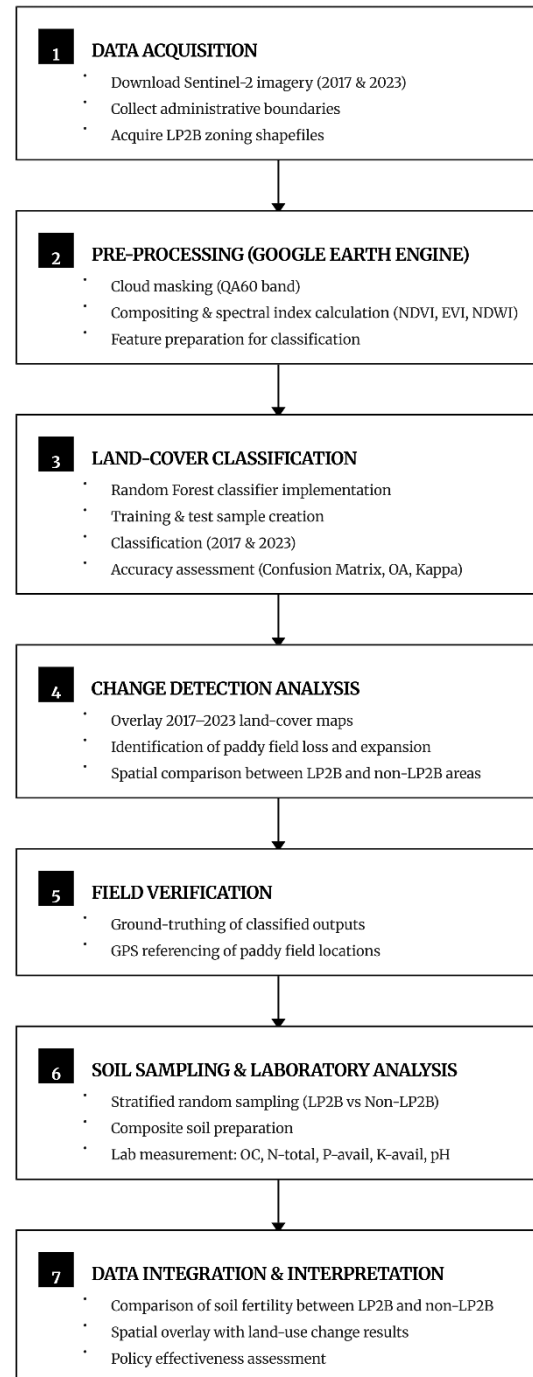
Paddy field land cover maps for 2017 and 2023 were generated using the Random Forest (RF) classification algorithm within GEE (Belgiu & Drăguț, 2016). Input features for the RF classification included Sentinel-2 spectral bands, Sentinel-1 backscatter data, and derived vegetation indices. The overall classification accuracy was confirmed at 91.2% for 2017 and 89.8% for 2023, satisfying the technical rigor requirement for land use studies. Change detection analysis was performed between the two time points to precisely identify areas categorized as paddy loss, stable paddy, or new paddy formation.

## 2.4. Soil Sampling and Laboratory Analysis

A field campaign was conducted to collect and analyze soil samples from two distinctly defined geospatial zones: (1) stable paddy fields inside the LP2B boundaries; and (2) newly expanded paddy fields located outside the LP2B boundaries (Non-LP2B Expansion).

A total of 30 composite soil samples were collected, with 15 sample locations (n=15) in each zone (LP2B and Non-LP2B expansion). To ensure representative data, each sample location comprised a composite sample gathered from 5 random sub-sample points within a 5-meter radius. Sampling occurred in the plow layer (0–20 cm depth).

Key soil fertility indicators analyzed include: Organic Carbon (Walkley and Black method), Total Nitrogen (Kjeldahl method), Available Phosphorus (Bray-1 method), Exchangeable Potassium (Ammonium Acetate pH 7), and soil pH. An independent samples t-test was conducted to statistically compare the mean values of key nutrient indicators between the LP2B and Non-LP2B land categories to test for stringent quality differences.



**Figure 2.** Research Methodology Flowchart

### 2.5. Zonal Analysis and Spatial Pattern Assessment

The land change detection results were subjected to zonal analysis using the official LP2B boundary file. Area calculations for each change class (loss, stable, gain) were determined precisely in hectares. An additional spatial analysis was performed to identify potential key drivers behind conversion pressures. This involved generating a 500m buffer around existing road networks and overlaying this buffer with the map of paddy loss within the LP2B zone. This step served to operationally define the infrastructure pressure zone.

**Table 1.** Distribution of Paddy Field Change (ha) 2017-2023

Location	Paddy Field Loss (ha)	Stable Paddy Field (ha)	New Paddy Field (ha)	Net Change (ha)
Inside LP2B	23.76	30,512.43	0.00	-23.76
Outside LP2B	891.47	21,780.12	5,141.77	+4,250.30
Total	915.23	52,292.55	5,141.77	+4,226.54

Conversely, a substantial expansion of 5,141.77 ha of new paddy fields occurred outside the LP2B areas, resulting in a massive net increase in the unprotected zone. This spatial divergence strongly supports the presence of a "leakage effect" (Verburg et al. 2015), where protective regulations applied to one area inadvertently shift and intensify agricultural expansion and development pressure in neighboring, unprotected zones.

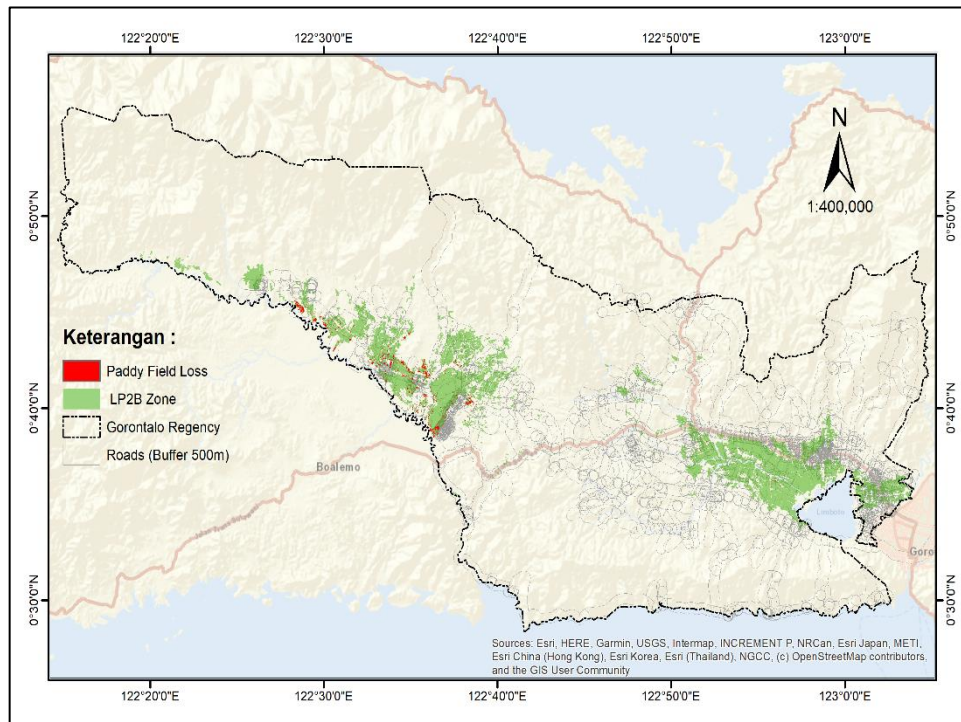
Further spatial analysis identified a primary spatial catalyst behind the observed LP2B loss. Conversion within

## 3. Results and Discussion

### 3.1. Policy Effectiveness and Spatio-Temporal Dynamics

The land change analysis reveals a significant policy paradox in Gorontalo Regency between 2017 and 2023 (Table 1). In aggregate, the total paddy field area showed a net increase of 4,226.54 ha. However, the legally protected LP2B zones suffered an undeniable net paddy field loss of 23.76 ha.

the protected area was not spatially random; remarkably, 82.1% of the total observed paddy loss inside the LP2B occurred within a 500m radius of existing road networks. This finding aligns with urban economic theory, which identifies infrastructure development as a key driver of land value appreciation and subsequent conversion pressure (Bryan et al., 2016; Zheng, Huang, Feng, & Xiao, 2021), highlighting a significant enforcement weakness along infrastructure corridors (Figure 3).



**Figure 3.** Map of Spatial Paddy Conversion Patterns and Road Network

### 3.2. Comparative Assessment of Soil Natural Capital

Field sampling and laboratory analysis provide critical

qualitative context to assess the real cost of land conversion.

Table 2 presents a comparison of the key soil fertility

indicators, representing the land's natural capital, between stable LP2B areas and the newly converted expansion areas outside LP2B.

**Table 2.** Comparison of Mean Soil Fertility Indicators (0–20 cm) Between LP2B and Non-LP2B Zones

Indicator	Unit	LP2B (Mean ± SD)	Non-LP2B Expansion (Mean ± SD)	Difference (%)	Statistical Classification (LP2B)	Statistical Classification (Non-LP2B)
pH (H <sub>2</sub> O)	-	6.51 ± 0.12	5.89 ± 0.21	+10.5	Neutral	Slightly Acidic
Organic Carbon	%	3.15 ± 0.45	1.88 ± 0.38	+67.6	High	Medium
Total Nitrogen	%	0.28 ± 0.05	0.15 ± 0.03	+86.7	Medium	Low
Available Phosphorus (Bray-1)	ppm	18.7 ± 2.1	10.5 ± 3.4	+78.1	medium	Low
Exchangeable Potassium	cmol(+)/kg	0.45 ± 0.07	0.22 ± 0.05	+104.5	Medium	Low

\*Note: Soil fertility values represent 15 composite samples per category. The differences for OC and TN were statistically significant ( $p < 0.01$ ) based on the independent samples t-test. Soil quality classification (High, Medium, Neutral) refers to the Technical Guidelines for the Implementation of Soil Fertility Research from Badan Penelitian dan Pengembangan Pertanian (Purwanto et al., 2014).

The comparative analysis empirically confirms that the soils within the established LP2B areas are intrinsically and significantly superior in quality. The LP2B zones showed statistically significantly higher mean levels for Organic Carbon (3.15% vs. 1.88%) and Total Nitrogen (0.28% vs. 0.15%). The newly developed lands outside LP2B generally fall into the Medium or Low fertility categories for these vital indicators.

### 3.3. Quality Versus Quantity: The Real Cost of Policy Failure

The integration of geospatial and soil analysis introduces a critical dimension to the evaluation of LP2B policy effectiveness: the conversion pattern that occurred resulted not merely in a simple area loss, but in a disproportionate depletion of the most valuable soil natural capital. The loss of 23.76 ha inside the LP2B zone is qualitatively magnified because this land possessed superior intrinsic resilience and productivity.

Conversely, the substantial area expansion that occurred outside the protected zones represents production on marginal land, as evidenced by the inferior nutrient content (Table 2). This substitution of quality for quantity highlights a major flaw in sustainable land management (Liu et al., 2013).

This finding is consistent with Fitri et al. (2022), who also reported a significant degradation in soil nutrient quality following paddy field conversion in West Java. Similarly, studies in peri-urban Asia (Zheng et al., 2021) suggest that converted lands near transport corridors consistently show lower natural fertility. The failure of the LP2B policy in Gorontalo is a *discriminatory* failure—namely, only the highest natural capital lands were lost. A crucial weakness in the implementation of Law No. 41/2009 is the lack of adequate fiscal incentives and a robust institutional framework ensuring inter-agency coordination, particularly between LP2B zoning and

infrastructure planning.

To move beyond simple area accounting, this study formally suggests the development of a Weighted Land Loss Metric (WLLM). By using soil fertility metrics, such as Organic Carbon content, as a weighting factor, future policy assessments can quantitatively demonstrate the real cost of conversion and the irreversible depletion of natural capital.

In addition to having implications for long-term soil quality degradation, rice expansion into marginal land also has the potential to increase dependence on external inputs, especially chemical fertilizers. Fields with low OC and N content require higher fertilizer doses to achieve optimal productivity. Increased application of nitrogen and phosphorus fertilizers in this context is often associated with the risk of surface water pollution through run-off, which can accelerate the eutrophication of irrigation canals and surrounding water bodies. These findings confirm that expansion into marginal land not only has an agronomic impact, but also creates environmental pressures that need to be considered in the management of agricultural areas.

## 4. Conclusion

This study has a number of limitations that need to be noted. First, the analysis of land change is carried out ex-post based on two discrete time points (2017 and 2023). This approach is effective for assessing aggregate changes, but it has not been able to capture more subtle temporal dynamics, such as annual fluctuation patterns, seasonal disturbances, or sudden change events. Future studies suggest applying continuous time series monitoring methods, such as Breaks For Additive Season and Trend (BFAST) or Continuous Change Detection and Classification (CCDC), to identify land changes more dynamically and precisely.

Second, although this paper links the ineffectiveness of LP2B to development pressures and weak enforcement, this

study has not explored in depth the socio-economic and micro-institutional factors that encourage farmers to sell or convert LP2B land. Factors such as household liquidity needs, land market pressures, short-term incentives, and relationships with village officials can play a significant role in influencing policy compliance. Such micro-analyses have the potential to enrich understanding of the causes of non-compliance and strengthen the formulation of policy interventions at the local level.

This study successfully evaluated the effectiveness of the LP2B policy in Gorontalo Regency by integrating the spatio-temporal analysis of paddy field change (2017–2023) with an assessment of intrinsic soil fertility. The empirical findings reveal a critical policy paradox: despite an aggregate net increase in agricultural area across the regency, the legally designated LP2B zones suffered an undeniable net loss of 23.76 hectares of paddy field. The lost LP2B land was proven to possess superior soil natural capital, characterized by significantly higher levels of Organic Carbon and Total Nitrogen, compared to the lower-quality soil utilized for expansion outside the protected boundaries.

These findings hold profound theoretical and practical implications. Theoretically, the study reinforces land system science by providing empirical evidence of how passive legal instruments, when confronted with intense development pressures, lead to unintended leakage effects and the detrimental substitution of high-quality resources with inferior ones.

For policymakers, this study recommends the integration of soil quality-based zoning, strengthened

enforcement around road corridors, and the adoption of incentive mechanisms to retain high-fertility agricultural land. Future policies must focus interventions on high-risk transition zones. Furthermore, the adoption of a Weighted Land Loss Metric that incorporates soil quality indicators is essential for providing a more accurate assessment of policy failure beyond simple quantitative area counts.

While this study provides critical contributions, it is limited by its reliance on two discrete time points for change detection. Future research should prioritize dynamic and continuous monitoring approaches and delve deeper into the specific local socio-economic and institutional drivers contributing to policy non-compliance within the LP2B zones. As a two-point based ex-post study, this study recommends the use of continuous time series analysis to improve the temporal resolution of land change detection in subsequent studies.

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