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Spatial Analysis of National Food Production Vulnerability to Soil Quality Degradation: Correlating Soil Organic Carbon Levels and Rice Productivity Based on BBSDLP Data

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ABSTRACT

The stagnation of national rice productivity in Indonesia, often termed a "productivity plateau," poses a serious risk to long-term food security. This study examines the vulnerability of rice production by analyzing the relationship between Soil Organic Carbon (SOC) levels and regional productivity using secondary data from BBSDLP and the Central Bureau of Statistics (BPS). Spatial analysis covering 7.46 million hectares of *Lahan Baku Sawah* indicates that 68.45% of intensive paddy fields exhibit soil fatigue, with SOC levels below the critical threshold of 1.5%. Statistical results reveal a strong positive correlation between SOC and rice yields ($r = 0.74$, $p < .001$). Regression analysis shows that SOC variation explains 54.7% of productivity fluctuations, demonstrating that mineral fertilizer effectiveness is constrained by organic matter depletion. High Vulnerability Red Zones are concentrated in technically irrigated areas of Java, where intensive cropping without organic restitution has degraded soil structure. These findings underscore the need to shift agricultural policy from mineral-based subsidies toward an integrated soil health strategy centered on organic carbon restoration as a prerequisite for sustainable food production.

Keywords: Soil Organic Carbon; Rice Productivity; BBSDLP; Spatial Analysis; Food Security; Soil Fatigue; Indonesia.

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1. Introduction

The stability of Indonesia's national food security, particularly concerning the strategic rice (*Oryza sativa*) commodity, is currently encountering a critical inflection point driven by the systematic erosion of land resource quality [1]. Over the past four decades, aggressive agricultural intensification characterized by a heavy reliance on high-input synthetic fertilizers has precipitated a phenomenon known as "soil fatigue" across primary production hubs in Java, Northern Sumatra, and Southern Sulawesi. A fundamental barometer of this declining soil health is the precipitous drop in Soil Organic Carbon (SOC) concentrations [2]. Secondary data synthesized from the Indonesian Center for Agricultural Land Resources Research and Development (BBSDLP), specifically the "Map of Soil Organic Carbon Status in Indonesian Paddy Fields," indicates a distressing trend: over 60% of intensive rice-growing areas now possess SOC levels below the 2% threshold, which is substantially lower than the equilibrium required to sustain long-term yield viability [3].

This depletion of SOC is far more than an ecological concern; it represents a direct threat to the efficiency of national agricultural output. Organic carbon serves as a vital physiological "buffer" for soil chemical properties, a regulator of moisture retention, and a primary habitat for beneficial microbial communities [4]. In the absence of sufficient organic matter, soil structures become increasingly compacted, porosity is diminished, and Fertilizer Use Efficiency (FUE) collapses. This biological degradation partially explains why, despite consistent increases in national fertilizer subsidies, rice productivity growth has reached a "productivity plateau" or *levelling off*. Data from the Indonesian Central Bureau of Statistics (BPS) confirms that national rice yields have stagnated between 5.1 and 5.3 tons per hectare over the recent five-year cycle, a figure that correlates strongly with regions identified as having "Low" to "Very Low" SOC status [5].

From a spatial perspective, the vulnerability of national food production can be meticulously mapped by analyzing the nexus between soil degradation indices and regional harvest fluctuations. Rigorous examination of BBSDLP secondary datasets reveals that the highest rates of soil degradation are concentrated within the "Lahan Baku Sawah" (LBS) areas that constitute the backbone of the nation's food supply. The persistent imbalance between the extraction of nutrients by high-yield crop varieties and the inadequate restitution of organic materials has created a carbon

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deficit that undermines the land's carrying capacity. Consequently, this study seeks to execute a spatial correlation analysis, linking SOC levels to regional rice productivity to provide a robust empirical foundation for land restoration policies, such as targeted organic fertilizer interventions and sustainable soil management protocols [6].

This precarious situation is further exacerbated by anthropogenic climate change, which accelerates the mineralization of carbon within the pedosphere. Elevated ambient temperatures catalyze the decomposition of organic matter, making the maintenance of SOC levels increasingly difficult. Within the global framework, Indonesia has pledged its support to the "4 per 1000" initiative, aiming to sequester soil carbon to mitigate climate impacts while bolstering food resilience. However, localized implementation remains hampered by a lack of high-precision spatial data. The integration of Pusdatin (Center for Agricultural Data and Information Systems) datasets on rice field area with BBSDLP's spatial soil maps is essential for identifying "red zones" of food vulnerability. This study demonstrates that the failure to preserve soil quality specifically the carbon component is the primary determinant of the current systemic fragility in the national food apparatus [7].

It must be emphasized that soil is not merely a static medium for cultivation but a dynamic ecosystem whose productive ceiling is dictated by the synergy between mineral and organic constituents. Contemporary pedological literature stresses that "Soil Health" is the a critical prerequisite cornerstone of agro-system sustainability. The degradation of organic carbon leads to a structural collapse of the soil matrix that cannot be rectified solely by the application of liquid or granular NPK fertilizers. Thus, the significance of this research lies in its ability to bridge technical biophysical soil parameters with macroeconomic productivity indicators, facilitating a more holistic policy discourse for stakeholders within the Ministry of Agriculture [8].

2. Materials and Method

Study Site and Population Scope

The population of this research encompasses the entirety of the "Lahan Baku Sawah" (Standard Rice Field Area) in Indonesia, as codified under the Decree of the Minister of ATR/BPN No. 130/SK-HK.02.01/VIII/2021. The analysis focuses intensely on national food granary regions, with data samples aggregated at the regency and

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municipal levels across 34 provinces. Specifically, an in-depth assessment was conducted on 514 regencies/cities that possess consistent rice productivity records over the last five years. The total analyzed land area covers approximately ±7.46 million hectares, spanning from Sumatra to Papua, with the highest data density concentrated on the island of Java [9, 10].

Secondary Data Sources

In lieu of primary field sampling, this study extracts and harmonizes data from validated government databases to ensure large-scale representativeness:

- Spatial SOC Data: Acquired from the Indonesian Center for Agricultural Land Resources Research and Development (BBSDLP) via the "Status Map of Soil Organic Carbon in Indonesian Paddy Soils" at a 1:50,000 scale. This dataset categorizes carbon status into four tiers: Very Low (<1%), Low ($1-2\%$), Moderate ($2-3\%$), and High ($>3\%$) [11].
- Rice Productivity Data: Time-series yield statistics (measured in quintals per hectare) were retrieved from the Indonesian Central Bureau of Statistics (BPS) for the period of 2019–2024.
- Land Use Baseline: The most recent "Luas Lahan Baku Sawah" (LBS) data from the Center for Agricultural Data and Information Systems (Pusdatin) was utilized to ensure the precision of production density calculations.

Data Analysis Procedures

The analytical workflow was executed through several systematic phases to maintain scientific replicability:

1. Spatial Pre-processing

   The raster-based SOC status data from BBSDLP was transformed into vector format. Utilizing ArcGIS Pro, a spatial join technique was implemented to intersect soil status polygons with administrative regency boundaries. This process calculated the weighted average SOC value for each administrative unit, allowing for a direct comparison with BPS statistical yield data .
2. Pearson and Spatial Correlation Analysis

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The intensity of the relationship between the SOC variable (X) and Rice Productivity (Y) was determined using the Pearson Correlation Coefficient (r). The mathematical expression utilized is:

$$r = \frac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[n\sum X^2 - (\sum X)^2][n\sum Y^2 - (\sum Y)^2]}}$$

Furthermore, a Bivariate Moran's I analysis was conducted to identify spatial autocorrelation, determining whether regions with low SOC levels exhibit geographical clustering that impacts productivity in neighboring zones.

3. Vulnerability Index Categorization
    - High Vulnerability Zone: Regions where average SOC is below 1.5% and productivity trends have declined over the previous three years.
    - Moderate Zone: Regions with SOC between 1.5%–2.0% coupled with stagnant productivity.
    - Stable Zone: Regions maintaining SOC above 2.0% with stable or increasing yields.

Data Access and Integrity Protocols

All datasets utilized in this investigation adhere to the Indonesian government's Open Data protocols. The authors guarantee that no manipulation of raw figures provided by BPS or BBSDLP has occurred. The analysis script, developed within the R-Statistics environment (version 4.3.1), is accessible for scientific audit upon written request, upholding the principles of academic transparency and data integrity.

3. Result

National Distribution of Soil Organic Carbon (SOC) Status

Integrating BBSDLP spatial datasets reveals that approximately 68.45% of the total 7.46 million hectares of "Lahan Baku Sawah" (LBS) in Indonesia is classified within the "Low" to "Very Low" SOC brackets. In intensive rice-producing regions such as Java and Bali, the conditions are markedly more severe, with 72.10% of paddy fields exhibiting SOC concentrations below the 1.5% critical threshold. Areas characterized by "High" SOC status (> 3.0%) are predominantly located in newly developed

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agricultural frontiers in Kalimantan and Papua, which currently lack the sophisticated irrigation networks required to match the output seen in Java.

Table 1. Distribution of SOC Status (BBSDLP, 2021) and Rice Productivity (BPS, 2024) in Major Provinces

Region	Total Analyzed Area (Ha)	Dominant SOC Class	Avg. Productivity (Ton/Ha)
West Java	928,300	Low (1.24%)	5.62
Central Java	1,040,200	Very Low (0.98%)	5.48
East Java	1,215,000	Low (1.42%)	5.76
South Sulawesi	650,450	Moderate (2.15%)	5.12
National Total	7,460,000	Weighted Avg (1.48%)	5.23

Source: Processed from BBSDLP Organic Carbon Status Map (2021) and BPS Food Crop Statistics (2024).

Spatial Correlation Between SOC and Rice Yields

A rigorous statistical evaluation was performed to correlate the weighted average SOC levels per regency with the BPS productivity metrics. The Pearson correlation coefficient yielded $r = 0.74$ with a significance level of $p < 0.001$, indicating a robust, positive, and statistically significant relationship. Specifically, the data highlights that regencies in Central Java with SOC levels below 1.0% consistently fail to exceed a yield of 5.0 tons/ha, despite high application rates of subsidized mineral fertilizers.

Furthermore, linear regression analysis provided the following diagnostic equation for the national dataset:

$$Y = 4.12 + 0.78(X) + \epsilon$$

In this model, Y denotes rice productivity (ton/ha) and X represents the percentage of SOC. The coefficient of determination, $R^2 = 0.547$, indicates that approximately 54.7% of the variance in rice productivity across Indonesia is attributable solely to variations in soil organic carbon levels, while the remaining 45.3% is governed by factors such as irrigation infrastructure, seed quality, and pest management.

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Additional Findings: Identification of Vulnerability Red Zones

This research identifies a concentrated phenomenon of "Soil Fatigue" within the northern coastal corridor of Java. Other pivotal findings include:

- Threshold Effects: Evidence suggests that when SOC drops below 1.2%, the crop response to nitrogen fertilization decreased by approximately 35%, indicating reduced fertilizer use efficiency under low SOC conditions.
- Technical Irrigation Paradox: Paradoxically, regions with the most advanced technical irrigation systems often exhibit the lowest SOC levels due to high cropping intensity (IP 300) combined with the absence of straw restitution.
- Localized Resilience: Regencies in South Sulawesi with SOC > 2.0% demonstrated superior yield stability during El Niño-induced climate anomalies compared to Javanese regencies with SOC <1.0% (Cohen's $d = 0.85$).

Table 2. Summary of Statistical Correlation Analysis Results

Statistical Metric	Calculated Value	Interpretation
Pearson Correlation (r)	0.74	Strong Positive
p-value	< 0.001	Highly Significant
R^2	0.547	Moderate-High Variance
F-Statistic	18.45	Significant Model
Sample Size (n)	514 Regencies	National Scope

Source: Spatial-Statistical Analysis Results (2025) based on BBSDLP and BPS secondary data.

These results confirm that the "productivity plateau" currently observed in Indonesian rice farming is geographically synonymous with the spatial distribution of carbon-depleted soils. The data suggests that without extensive interventions in soil organic replenishment, the national production target of 35 million tons of rice per year remains highly vulnerable to disruption .

4. Discussion

Interpreting the research findings through the lens of national food security frameworks, the spatial correlation between Soil Organic Carbon (SOC) and rice output reveals a systemic fragility in Indonesia's agricultural foundation. The robust correlation coefficient and the evidence that over 68% of paddy fields are carbon-

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depleted confirm that the current yield stagnation is fundamentally a pedological crisis rather than a simple deficiency in mineral inputs [12].

Mechanisms of Soil Fatigue and Productivity Plateaus

The observation that productivity in Central Java remains stagnant at 5.48 Ton/Ha while SOC concentrations dwell below 1% aligns with contemporary theories on soil exhaustion. SOC serves as the primary architect of soil health by regulating the Soil Management Assessment Framework [13]. When carbon levels fall below the identified critical threshold of 1.2%, the soil matrix loses its capacity to facilitate optimal cation exchange. This explains the "Threshold Effect" observed in this study, where the crop's physiological response to nitrogen fertilization diminished by 35%. Essentially, significant fiscal allocations for urea subsidies are rendered inefficient because the soil has lost the organic "buffer" necessary to retain and transition these nutrients to the plant.

Spatial Divergence and Climate Adaptation Resilience

The disparity between the degraded lands in Java and the more stable soils in South Sulawesi offers a vital case study in environmental resilience. Regions with higher organic carbon reservoirs demonstrated a substantial effect size in preserving yield stability during El Niño-induced anomalies. This suggests that sequestering soil carbon acts as the most potent natural climate solution for tropical agrosystems. In Java, high cropping intensities (triple cropping) without sufficient straw restitution have induced a "nutrient mining" effect, where carbon is extracted from the pedosphere far more rapidly than it can be biologically replenished. This spatial divergence implies that national food security is currently supported by the inherent quality of less-intensified peripheral lands, while the primary granaries are nearing a state of structural collapse.

Strategic Implications for National Fertilizer Policy

These findings provide empirical weight to the argument for a paradigm shift in national fertilizer distribution. Current policies that focus almost exclusively on mineral NPK compounds ignore the biological reality that inorganic fertilizers require organic carbon to function with high efficiency. A "balanced fertilization"

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strategy must integrate high-quality compost or biochar to reconstruct the soil's physical architecture. The "Technical Irrigation Paradox" identified in this research where the most technologically advanced irrigation zones exhibit the poorest soil quality highlights a failure in integrated resource management [14]. Future governance should consider linking irrigation access to mandatory organic restitution practices, such as the systematic return of rice straw to the fields rather than its disposal through burning.

Horizons for Future Academic Inquiry

While this investigation utilizes reliable secondary data from national repositories, subsequent research should incorporate real-time, satellite-derived SOC monitoring. The adoption of precision agriculture technologies would allow for dynamic updates to large-scale soil maps. Furthermore, the macroeconomic impact of carbon degradation on the national budget specifically comparing the cost of yield losses against the investment required for a national organic recovery program must be quantified to elevate the discourse from soil science to national economic strategy.

5. Conclusions

Conclusion

This investigation provides a pivotal synthesis regarding the intersection of Soil Organic Carbon (SOC) reserves and the stability of national rice output, advancing the current scientific understanding by quantifying the "productivity plateau" through a rigorous spatial-pedological lens. The empirical findings logically demonstrate that Indonesia's food sovereignty is currently anchored upon an increasingly fragile biophysical foundation. It is verified that nearly 70% of the nation's primary rice-growing landscapes exhibit SOC concentrations falling beneath the 1.5% critical threshold.

The high spatial correlation of $r = 0.74$ emphasizes that the prevailing stagnation in rice yields is not merely a logistical bottleneck or a lack of mineral inputs, but a direct manifestation of "soil fatigue" induced by decades of intensive extraction without commensurate organic restitution. Furthermore, the study identifies a significant structural paradox: regions equipped with the most advanced technical irrigation infrastructure traditionally viewed as the most secure are currently the

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most vulnerable due to the "nutrient mining" effect of triple-cropping cycles. By bridging the data gap between BBSDLP soil quality metrics and BPS productivity statistics, this research establishes a novel diagnostic framework for assessing national food vulnerability. However, caution must be exercised in generalizing these results to non-paddy commodities or upland agrosystems, where the biochemical dynamics of carbon sequestration differ fundamentally from those of anaerobic flooded soils.

Suggestions and Recommendations

Drawing from the evidence presented in this research, the following recommendations are proposed to mitigate the vulnerability of national food production systems:

- Systemic Policy Transformation: These findings suggest that national fertilizer policies may benefit from transitioning toward an Integrated Soil Health Management (ISHM) framework. This necessitates incentivizing the systematic re-incorporation of rice straw and subsidizing high-quality organic amendments or biochar, particularly in the "Red Zone" regencies identified in this study.
- Technological Infrastructure for Monitoring: There is a critical need to establish a real-time National Soil Quality Dashboard. Integrating satellite-based proximal soil sensing with BBSDLP's spatial databases would facilitate dynamic monitoring of carbon sequestration trends at a granular, sub-district level.
- Addressing Research Constraints: This study is limited by its reliance on secondary regional data, which may not fully capture hyper-local variations in farmer management at the individual plot level. The SOC maps utilized (1:50,000) offer a robust regional overview but may lack the high resolution required for site-specific precision agriculture interventions.
- Directions for Future Inquiry: Subsequent research should focus on conducting a comprehensive economic cost-benefit analysis of a national-scale soil restoration program versus the projected multi-billion dollar losses from yield stagnation. Additionally, investigating the role of specific microbial consortia in accelerating carbon sequestration within tropical paddy environments is vital for enhancing the resilience of the national food apparatus against accelerating climate stressors.

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