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MORALITY BEFORE KNOWLEDGE

Analysis of the impact of soil degradation on national food security from an environmental and sustainability perspective

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ABSTRACT

Background: Soil degradation poses a severe threat to national food systems, yet it is rarely integrated explicitly into national resilience policy frameworks. **Methods:** This study examines the structural relationship between soil degradation dynamics and national food security capacity in Indonesia from a socio-ecological perspective. Utilizing a descriptive-qualitative approach with secondary data triangulation across datasets from KLHK, BPS, and the National Food Agency (BPN), this paper maps cross provincial variations in critical land area against regional Food Security Index (FSI) outcomes. **Findings:** The findings reveal a clear negative linear correlation; highly degraded regions such as East Nusa Tenggara and West Kalimantan register low FSI scores (<65) due to severe erosions and stagnant primary crop (rice and maize) productivity. Conversely, environmentally stable zones like DI Yogyakarta maintain high food security (>80) supported by strong institutional adaptive capacity. **Conclusion:** In conclusion, transitioning from conventional input-intensive farming to structured agro-ecological restoration frameworks is vital to reverse soil degradation, optimize long-term crop yields, and secure national food sovereignty against escalating climate uncertainties. **Novelty of this study:** While this study is limited by its reliance on macro-level secondary data without primary field sampling or spatial inferential modeling, its core novelty lies in positioning soil health nor merely as an agronomic variable, but as a baseline pillar for systemic national resilience planning. Ultimately, this study transitions the discourse toward an actionable, policy focused frameworks that integrates soil conservation metrics into long term national security paradigms to safeguard and adaptive and equitable food system.

KEYWORDS: food security index; Indonesia; national resilience; soil degradation; sustainable agriculture.

1. Introduction

Soil is a foundational component of terrestrial ecosystems, serving as the primary medium for plant growth and agricultural productivity. Healthy soil resources are inherently linked to sustainable biomass production, human welfare, and long-term food security (Kopittke et al., 2024). In Indonesia, institutional efforts to mitigate soil degradation have been codified under Government Regulation No. 150 of 2000, which establishes standard criteria and assessment methods for soil quality based on physical, chemical, and biological shifts. However, despite existing regulatory frameworks, soil

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degradation remains a critical, multidimensional threat. Globally, the FAO (2023) reports that over 33% of the world's land faces moderate to severe degradation, with potential escalation to 95% by 2050 if conservative interventions are omitted. For an agrarian reliant nation like Indonesia, this global trajectory manifests as a pressing systemic risk, where a population projected to reach 319 million by 2045 demands heightened food production from increasingly compromised land resource (BPS, 2020; Salasa, 2021).

The current trajectory of land degradation in Indonesia presents alarming trends. According to the Ministry of Forestry (Kemenhut, 2024), critical land area has reached approximately 12 million hectares, signifying a severe decline in ecological carrying capacity across various provinces. This ecological decline is compounded by anthropogenic pressures such as land conversion and unsustainable agriculture intensification as well as global climate change, which accelerates erosion and reduces the soil's capacity to retain nutrients and water (D'Odorico & Ravi, 2023; Edwin et al., 2023). While comparative regional insight indicate that tropical peers like India and Vietnam suffer similar productivity bottlenecks due to soil depletion (Bhattacharyya et al., 2023; Phuong & Choudhury, 2025), Indonesia's unique archipelagic vulnerability requires localized socio-ecological scrutiny to understand how localized soil degradation cascades into macroeconomic vulnerabilities.

While extensive literature has explored the traditional soil food nexus in Indonesia (e.g. Chaireni et al., 2020; Edwin et al., 2023), existing studies predominantly approach the phenomenon through an environmental or agronomic lens. A significant conceptual gap remains: prior reviews rarely position soil degradation within national resilience frameworks or policy paradigms. In the context of non-traditional security, soil health is not merely an environmental variable; it acts as the baseline for socio-economic stability, institutional adaptive capacity, and systemic national resilience against external shocks. Consequently, there is an urgent need to explicitly articulate how soil degradation trend inform national level resilience planning and sector specific strategies within agriculture.

To address this gap, this study examines the structural relationship between soil degradation dynamics and national food security capacity in Indonesia using an integrative secondary data lens. Specifically, this research seeks to answer the following explicit questions: (1) How do cross-provincial variations in soil degradation and critical land area correlate with regional Food Security Index (FSI) outcomes in Indonesia?; (2) In what ways do non-soil confounding variables, such as regional governance capacity and market access, influence food insecurity in highly degraded zones?; (3) How can current empirical soil-food metrics be systematically integrated into national resilience frameworks to enhance long-term policy paradigms?. By answering these questions, this study connects environmental conservation with national policy frameworks, aligning its contributions with both national resilience strategy and global sustainable development paradigms, particularly Sustainable Development Goals (SDGs) Goal 2 (Zero Hunger) and Goal 15 (Life on Land). Ultimately, this analysis aims to transition the dialogue from a purely environmental review to actionable, resilience focused policy framework capable of securing an adaptive and equitable food system for Indonesia's future.

2. Methods

This study adopts a descriptive-qualitative approach utilizing secondary data triangulation to analyze the systemic relationship between soil degradation and national food security in Indonesia. This macro-level analytical framework integrates multi-institutional quantitative trends with qualitative policy assessments, allowing for a comprehensive evaluation of ecological pressures on the national food system without requiring field sampling. To ensure reliability and transparency, data were synthesized across multiple national ministries, international bodies, and academic repositories. Instead of a purely narrative description, the specific variables, temporal scales, and geographic coverage utilized in this study are systematically summarizes in Table 1.

Table 1. Summary of secondary data sources and variables

No	Variable/ Data Indicator	Institutional Source	Temporal Coverage	Geographic Scale
1	Critical Land Distribution	Ministry of Environment and Forestry (KLHK) & BPS	2006 – 2018	National & Provincial
2	Agricultural Production (Rice and Corn)	Central Bureau of Statistics (BPS)	2018 – 2024	National & Regional
3	Rice Field Surface Area Dynamics	Central Bureau of Statistics (BPS)	2003 – 2015	National & Regional
4	Regional Food Security Index (FSI)	National Food Agency (BPN)	2023	Provincial
5	Global Land Degradation Frameworks	Food and Agriculture Organization (FAO)	2015 – 2023	Global & Regional
6	Baseline Soil Degradation Criteria	Government Regulation (PP) No. 150/2000	2000 (Static)	Regulatory Landscape

The analytical workflow transitions through four distinct methodological phases to ensure data validity and minimize interpretative bias. The structured sequence of this research is illustrated in the analytical framework (Figure 1). To ensure high methodological clarity and address the complexity of the socio-ecological soil-food nexus, this study establishes a rigorous four-phase analytical framework, as visually delineated in Figure 1. Moving beyond a generalized qualitative overview, this structured approach ensures that the processing of multi source secondary data is transparent, veriable, and strictly aligned with study's analytical scope.

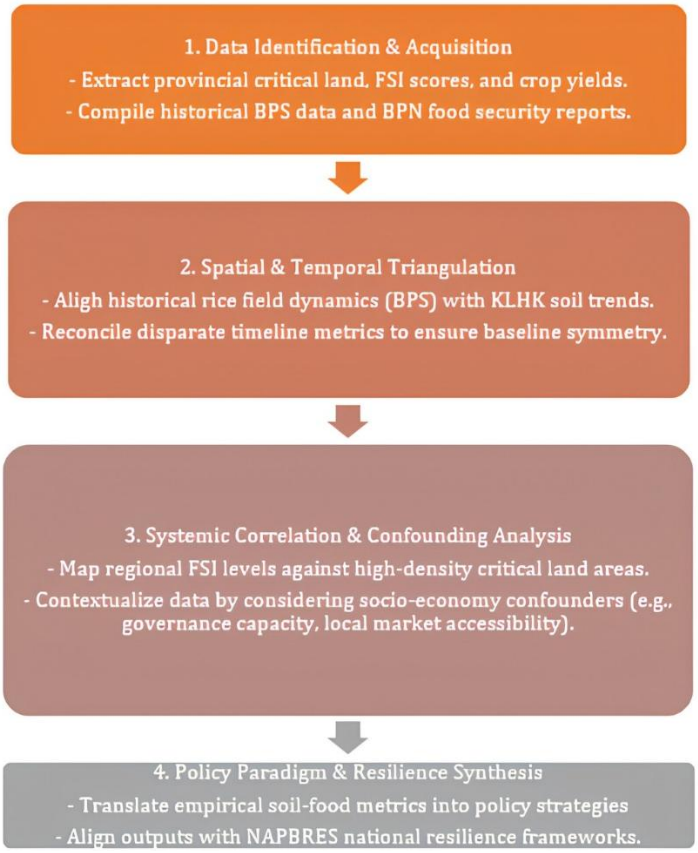

Fig 1. The analytical workflow

2.1 Phase 1: Multi source secondary data acquisition

The initial phase of the methodology involves systematic data harvesting from four primary, highly credible institutional repositories in Indonesia. First, baseline ecological datasets concerning critical land surface areas, localized soil degradation matrices, and historical soil organic matter depletion were retrieved from the Ministry of Environment and Forestry (KLHK) databases spanning the period of 2006-2018. Second, macro-regional agricultural outputs specifically the annual crop production volumes of staple commodities like rice (*Oryza sativa*) and corn (*Zea mays*), alongside agricultural chemical input ratios (NPK saturation) were gathered from the Central Bureau of Statistics (BPS) and the Ministry of Agriculture. Third, land use conversion dynamics, highlighting the systemic reduction of productive wetland and active rice field surfaces, were obtained from the Ministry of Agrarian Affairs and Spatial Planning (ATR/BPN) covering 2003-2019. Finally, socio-economic food security parameters were retrieved from the Food Security Agency (BKP) and the National Socio-Economic Survey (*Susenas*), focusing primarily on the 2022-2023 Provincial Food Security Index (FSI) scores.

2.2 Phase 2: Temporal data aggregation and harmonization

A critical methodological challenge in using multi source secondary data is the disparity in temporal scales and reporting frequencies. To resolve the specific concern regarding seasonal production data particularly from BPS agricultural reports a strict temporal data aggregation protocol was applied. Rather than evaluating raw, short-term seasonal fluctuations (such as sub-annual harvesting cycles or quarterly yield variations), all seasonal datasets were systematically aggregated into cumulative annual metrics. This harmonization ensures that the agricultural productivity data from 2018-2024 is strictly comparable on a year-by-year baseline with the long-term ecological degradation data. This temporal smoothing filters out temporary climatic anomalies (e.g., short-term El nino or La Nina impacts) and highlights the genuine, long-term structural trajectory of soil degradation affecting food security.

2.3 Phase 3: Institutional data triangulation and verification

To eliminate potential institutional reporting biases and ensure data comparability, phase 3 executes a rigorous qualitative triangulation protocol. Data validation was performed by cross referencing overlapping parameters across different institutional outputs. For instance, the land conversion rates reported by ATR/BPN were cross verified with the regional agricultural land allocation data provided by the Ministry of Agriculture and spatial changes recorded by KLHK. Furthermore, to eliminate mathematical or categorization gaps, spatial boundaries were normalized to the provincial level. This cross provincial alignment serves as an empirical foundation to safely compare physical ecological damage with institutional policy outcomes.

2.4 Phase 4: Confounding variable filtering and synthesis

The final analytical phase shifts from raw empirical correlation to deep theoretical synthesis. Recognizing that the physical relationship between soil degradation and food vulnerability is not entirely isolated, this phase integrates a screening mechanism for non-soil cofounding variables. Structural factors such as regional governance capacity, localized market infrastructure accessibility, and rural baseline poverty rates are systematically mapped alongside the physical soil data. This holistic filter prevents oversimplified ecological determinism, allowing the study to properly synthesize how socio-economic vulnerabilities interact with physical land degradation, ultimately generating robust, realistic policy pathways aligned with SGD 2 (Zero Hunger) and SGD 15 (Life on Land). To maintain research validity, rigorous data triangulation was performed by systematically cross-checking federal datasets against peer-reviewed international frameworks (FAO) and historical academic publications. The interpretive synthesis actively accounts for regional ecological diversities and institutional variances across Indonesia provinces, ensuring that the descriptive output directly informs national level resilience planning rather than remaining a purely environmental review.

3. Results and Discussion

3.1 Spatial and typological dynamics of soil degradation

Soil resources act as a strategic ecological baseline supporting sustainable food production across the Indonesian archipelago. Based on data from the Ministry of Environment and Forestry (KLHK) and BPS, the aggregate area of critical land reached approximately 14.01 million hectares. This degradation is driven by interconnected anthropogenic pressures, including forest to agriculture conversions, excessive inorganic inputs, and non-conservative tillage. Historical longitudinal assessments by Wahyunto & Dariah (2014), Kurnia et al. (2010), Atmojo (2006), and Hafif (2020) demonstrate that degraded agricultural areas expanded drastically from 18 million hectares in 1993 to 77.8 million hectares by 2007, primarily driven by uncontrolled accelerated erosion.

Spatially, Minister of Environment and Forestry Decree No. SK.306/MENLHK/PDASHL/DAS.0/7/2018 captures substantial regional imbalances. High concentrations of critical land are localized outside Java, led by North Sumatra (1.34 million ha), West Kalimantan (1.01 million ha), and South Sumatra (0.73 million ha). Conversely, Java Island experiences severe degradation characterized by extreme soil erosion exceeding 30 tons/ha/year in Central and East Java due to population density, urban expansion, and continuous agricultural intensification. This structural imbalance matches global observations by Bhattacharyya et al. (2023) in India, where high-yielding agro-ecosystems experience faster degradation than marginal zones due to nutrient overexploitation. As demonstrated in Figure 2, although macro-level data indicates a reduction in total critical land from 30.19 million hectares in 2006 to 14.01 million hectares by 2018, this decline does not automatically imply uniform soil quality recovery. New micro-zones of degradation continue to emerge due to rapid land conversion and inadequate soil-water conservation infrastructure.

Fig. 2. Trends in critical land area in Indonesia (2006-2018), (BPS, 2018)

3.2 Primary food production trends and agronomic imbalances

National food security capacity relies heavily on stable yields of primary staples, particularly rice and corn. However, seasonal production analyses reveal structural vulnerabilities. Based on Central Bureau of Statistics Data, national rice and corn outputs exhibit heavy climate dependency. Rice production drops to its lowest tier in January (21,950.26 tons), and peaks in March (90,827.28 tons), while corn reaches its apex in June (155,365.9 tons) and plunges in August (13,901.51 tons).

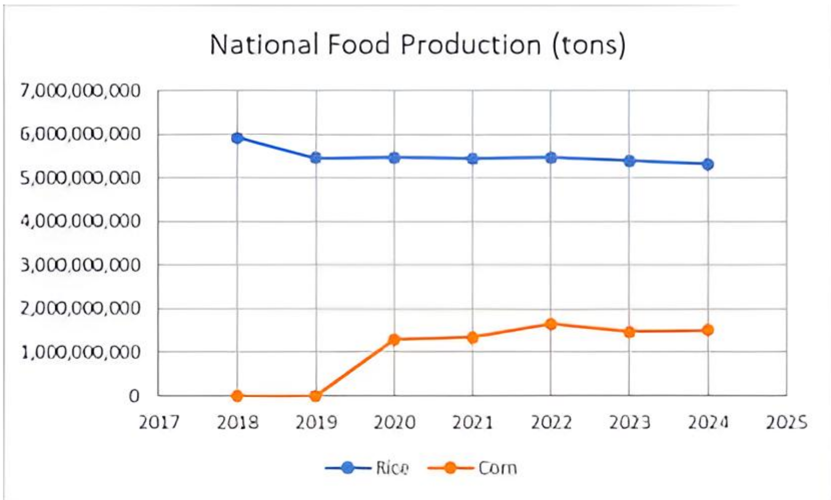

Fig. 3. National food production (rice and corn) in 2018-2024, (BPS, 2024)

This structural instability is compounded by an ongoing reduction in active rice field surface area, which fell from 7.876 million hectares in 2003 to 7.463 million hectares by 2019 (Decree of the Minister of ATR/BPN No. 686/2019). This stagnation highlights a critical efficiency gap: despite increasing input volumes, yields remain volatile due to severe physical, chemical, and biological degradation. Agronomically, Minarsih and Hanudin (2020) point out that the national NPK fertilizer application ratio stands at an imbalanced 10:3:1. This heavy nitrogen overloading reduces vital soil organic matter (SOM) and micronutrient availability (Zn, Cu, Fe), leading to chemical saturation. Such patterns reflect findings by Voltr et al. (2021) and Sharma et al. (2023), where highly degraded fields require up to 30% more mineral fertilizer input costs to generate identical baselines compared to uncompromised soils. Furthermore, high demographic dependency on rice which supplies 1,242 to 1,315 kcal/capita/day according to Susenas data creates systemic supply chain risks if soil health continues to decline.

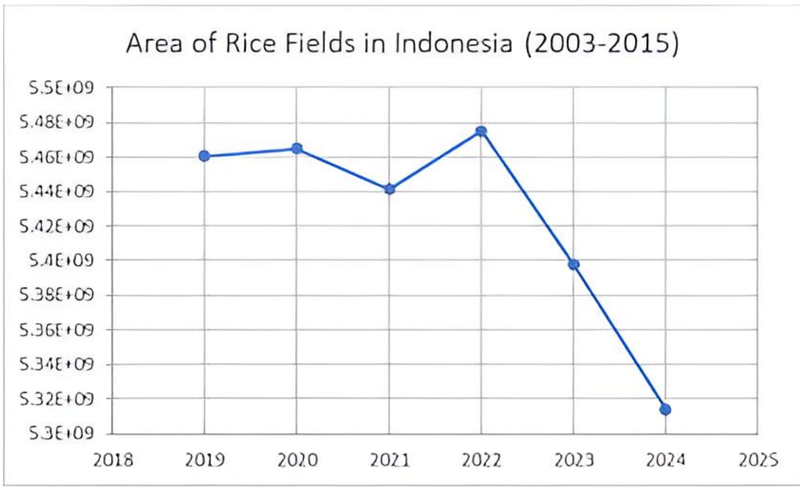

Fig. 4. Area of rice fields in Indonesia (2003-2015) (BPS, 2015)

3.2.1 Anthropogenic drivers and agronomic feedbacks of chemical saturation

The persistent agronomic imbalances observed in national primary food production trends are deeply rooted in long-term anthropogenic pressures and suboptimal extension frameworks. The heavily skewed national NPK fertilizer application ratio of 10:3:1 is not merely an isolated operational choice by smallholders. Rather, it reflects decades of structural state subsidies that historically favored nitrogen based inputs (urea) over potassium and phosphorus variants. From a soil chemistry perspective, continous and excessive nitrogen application triggers rapid soil acidification, which accelerates the leaching of essential base cations (Ca^{2+}, Mg^{2+}, K^{+}) and increases the bioavailability of toxic aluminium (Al^{3+}) species in highly weathered tropical soils. This chemical saturation actively disrupts the soil's biological equilibrum, suppressing beneficial microbial communities and mycorrhizal networks that are vital for natural nutrient cycling. As synthesized by Doberman & Witt (2000), this synthetic input depedency creates highly volatile agronomic feedback loop where farmers must continously escalate chemical dosages to maintain baseline crop yields, ultimately leading to permanent soil compaction and structural collapse. To break this destructive cycle, agricultural policies must pivot toward precision nutrient management schemes. Transitioning from uniform national input recommendations to site specific nutrient management (SSNM) frameworks allows for the customization of fertilizer applications based on localized provincial soil testing. Implementing these precision frameworks is essential to restore the biochemical intergrity of intensive farming systems, thereby stabilizing crop outputs againts escalating environmental stresses.

3.2.2 Microclimatic disruptions and crop vulnerability cascades

The structural degradation driven by chemical over saturation dosen not operate in isolation, it triggers severe microclimatic vulnerabilities within intensive agricultural fields. When soil organic matter depletes, the soil loses its thermal buffering capacity, causing extreme diurnal soil temperature fluctuations. During peak solar radiation hours, unprocted and compacted topsoils expereince rapid thermal spikes that directly suppress shallow root development and induce acute water stress in crops, even under scheduled irrigation. This localized thermodynamic instability alters the relative humidity within the crop canopy, establishing a highly favorable microclimate for opportunistic phytopathogenic outbreaks, such as blast disease (*Magnoporthe oryzae*) and brown planthopper infestations. Futhermore, as crops channel metabolic energy away from biomass production toward maintaining cellular osmotic balance under these stressed conditions, overall physiological resilience drops. This vulnerability cascade demonstrates that soil degradation is a compounding ecological threat that compromises systemic food supply chains, underlining the critical need to transition toward multi-trophic conservation management systems.

3.3 Systemic integration: Soil degradation and the Food Security Index (FSI)

3.3.1 Unpacking non-soil cofounding factors in the soil food nexus

To verify the direct relationship between ecological decline and national food availability, this study maps provincial critical land distribution against the 2023 Food Security Index (FSI) compiled by the National Food Agency (BPN). To satisfy empirical transparency and reproducibility, Table 2 structures this spatial correlation. While the spatial correlation presented in Table 2 strongly indicates that physical land degradation actively suppresses regional food security capacities, evaluating this nexus purely through an ecological lens risks oversimplifying complex socio-ecological realities. In practice, the intensity of the soil food security relationships is modulated, accelerated, or temporarily cushioned by three distinct non soil cofounding variables: regional governance capcity, localized market access, and historical institutional poverty rates.

Regional governance capacity serves as critical structural filter that determines how severely physical soil degradation translates into localized food insecurity. In provinces with high fiscal autonomy and strong institutional performance, such as DI Yogyakarta and Central Java, local governments possess the budgetary and administrative infrastructure include large-scale subsidized fertilizer distribution networks, institutionalized soil rehabilitation programs, and organized farmer field schools focusing on integrated pest management and organic soil matter restoration. Consequently, even in localized pockets where soil erosion or nutrient depletion is physically evident, the compounding threat to food availability is neutralized by efficient institutional buffers. Conversely, in regions characterized by low institutional capacity or fragmented agricultural extensions, such as parts of West Kalimantan or East Nusa Tenggara (NTT), governments often struggle to execute timely policy responses. In these administrative environments, bureaucratic bottlenecks delay the distribution of state subsidized agricultural inputs, leaving smallholder farmers highly vulnerable to immediate soil quality declines. Therefore, a low Food Security Index (FSI) score in a highly degraded province is frequently an indicator of combined ecological failure and institutional incapacity to govern rural resources effectively.

Table 2. Cross-provincial comparison of critical land areas and Food Security Index (FSI) outcomes

No	Selected Province	Critical Land Area (Million Ha)	2023 FSI Score	Food Security Status Classification	Primary Confounding / Ecological Factor
1	East Nusa Tenggara (NTT)	High Density (>0.50)	< 65.00	Vulnerable / Low	Arid climate, severe erosion, limited market infrastructure
2	West Kalimantan	1.01	< 65.00	Vulnerable / Low	Deforestation, peatland conversion, low organic matter
3	South Sumatra	0.73	68.50	Moderate	Intensive plantation expansion, structural input dependency
4	Central Java	Localized Erosion	78.20	Secure / High	Intensive farming, high fertilizer saturation, strong governance
5	DI Yogyakarta (DIY)	Low / Restored	> 80.00	Very Secure / High	High institutional adaptive capacity, advanced soil conservation

KLHK (2018), BPN (2022), and BPS (2024)

Beyond institutional governance, localized market accessibility and rural transport infrastructure represent a major socio-economic cofounder that distorts the direct correlation between soil fertility and food security. In many remote or archipelagic areas of Indonesia, the physical breakdown of soil systems is exacerbated by severe geographic isolation. For instance, an agricultural zone might possess moderately stable soil indicators, yet register an alarmingly low FSI score due to deficient logistical linkages. Poor road networks, high maritime transportation costs, and the absence of localized cold storage facilities prevent smallholder farmers from efficiently transporting harvested commodities to regional urban centers. This structural isolation triggers high post-harvest losses and dampens local farmgate prices, directly undermining rural household incomes and restricting economic food accessibility. On the other hand, in regions with highly integrated supply chains, such as the peri-urban agricultural clusters across Java, robust market access allows communities to import alternative food supplies seamlessly. In these highly connected systems, even if local agricultural soils suffer from physical compaction or chemical over saturation due to intensive multi-cropping, the local population rarely experiences acute food shortages because food products can be rapidly transported from surrounding surplus provinces. This proves that market connectivity can decouple local soil health from immediate food access, highlighting it as a mandatory variable in regional vulnerability mapping.

Finally, baseline structural poverty within rural farming communities heavily influences the trajectory of the soil food relationship. Soil conservation is inherently a capital-intensive endeavor, requiring upfront investments in high quality organic matter, biological fertilizer, erosion control structures, and sustainable drainage systems. In agrarian landscape dominated by extreme poverty and land fragmentation, smallholder farmers operate under severe liquidity constraints and high debt cycles. These economic pressure force farmers to prioritize short-term survival over long-term ecological stewardship, leading to over-exploitation of the land through continuous cropping cycles without adequate fallow periods. This creates a destructive feedback loop: initial poverty prevents investment in soil health, driving rapid land degradation, which subsequently collapses crop yields and plunges the household deeper into economic precarity. In this context, low FSI scores are fundamentally driven by poverty-induced barriers to sustainable technology adoption rather than a simple lack of physical land potential. Acknowledging structural poverty as a cofounding catalyst is essential for designing realistic mitigation strategies, as ecological policies that ignore the financial constraints of low-income smallholders are structurally predisposed to failure.

3.3.2 Land tenure insecurity and its impact on long-term soil investment

A frequently overlooked instituional confounder that heavily distorts the relationship between physical soil degradation and rural food security is the structural insecutiry of land tenure among Indoensian smallholders. In many agrarian sectors across Java and the outer islands, a significant precentage of foos producers operate either as tenant farmers, sharecroppers, or traditional landholders lacking formal, state-recognized land certificates. Theoretically, land tenure security serves as the primary economic incentive for long-term ecological stewardship. When smallholders face the constant threat of eviction or contractual termination, their operational horizon automatically shifts from long-term sustainability to short-term profit maximization. Consequently, tenant farmers are highly discouraged from investing their limited capital into expensive, slow-acting soil rehabilitation techniques such as organic matter incorporation, biochar stabilization, or constructing permanent agroforestry terraces which typically require several years to yield measurable financial returns. This economic behavior aligns with the institutional findings of Stiem-Bhatia et al., (2022), who observed that secure property rights are a mandatory precondition for widespread smallholder adoption of sustainable land management (SLM) practices.

In the context of Indonesia's agricultural policy, this tenure gap significantly weakens the efficacy of state-sponsored conservation programs. Government initiatives that distribute high quality organic fertilizers or promote agroforestry models often experience low adoption rates because the targeted farmers do not own the fields they cultivate. Indiscriminate chemical fertilizer over application becomes the default, economically rational strategy for these farmers, as it guarantees immediate, short-term harvest maximization before their land leases expire, even though it severely exacerbates long-term soil acidification and compaction. To resolve this structural bottleneck, national agricultural strategies must be strictly synchronized with the ongoing agrarian reform initiatives (Reforma Agraria) spearheaded by the Ministry of Agrarian Affairs and Spatial Planning (ATR/BPN). As emphasized by Otto (2009), formalizing land titles for low-income rural households does not merely enhance social equity; it provides the legal security necessary to unlock small scale green financing and incentivize grass-roots investments in soil carbon sequestration. Therefore, integrating land registration programs directly into environmental protection frameworks is vital to ensure that soil mitigation pathways can successfully foster both ecological resilience and regional food security.

As structured in Table 2, a clear negative linear pattern emerges between soil quality and regional food security capacity. Highly degraded provinces like West Kalimantan and NTT show low FSI values (<65), whereas environmentally stable zones like DIY maintain high scores (>80). However, to address alternative structural variables, this soil-food correlation is not entirely exclusive. Confounding socio-economic variables including regional governance capacity, localized market access, and baseline poverty rates often alter these outcomes. For instance, a province might experience severe physical soil degradation, but strong institutional funding and resilient market infrastructure can temporarily cushion domestic food accessibility.

Nevertheless, macro-level agronomic data indicates that severe soil organic matter depletion (<1.5%) causes a direct loss of up to 1.2 tons/ha in rice yield potential. According to Rahim et al. (2024), a localized 10% drop in staple yields triggers an 8% increase in regional market prices, which leads to a 3% to 5% drop in average household calorie intake among low-income brackets. Therefore, soil degradation acts as a strong multiplier of rural food insecurity.

3.4 Holistic mitigation pathways and national resilience frameworks

3.4.1 Technical and agronomic interventions

Vegetative soil conservation practices, such as agroforestry, cover cropping, and multi-cropping, are highly effective in reducing erosion. Empirical models by Pan et al. (2022) show that structural agroforestry can cut local erosions rates by up to 40% while adding 0.3% to soil organic matter annually. These methods can be paired with modern soil adjustments, such as biochar, compost, and biofertilizer, which improve cation exchange capacity and nutrients retention in degraded soils. In dryland regions like Nusa Tenggara, these vegetative practices should be supported by water saving tools, including organic mulching and localized drip irrigation, to optimize water use efficiency.

In adderessing the widespread depletion of soil organic matter (SOM) across Indonesia's primary agricultural landscapes, technical interventions must shift from superficial topsoil management to advanced, scientifically validated carbon restoration pathways. The integration of high stability organic amendments, particularly biochar devired from agricultural waste residues (such as rice husks, coconut shells, and oil palm empty fruit bunches), presents a highly effective strategy for long-term soil rehabilition. Biochar possesses a highly porous aroamatic structure that exhibits extreme resistance to microbial decomposition, enabling it to persist in tropical soils for centurien whilw significantly enhancing the soil's cation exchange capcity (CEC) and miosture retention properties. Empirical longitudinal models executed by Ramba et al., (2026) demonstrate that combining biochar applications with localized compost inoculations triggers a synergistic effect, accelerating the formation of stable soil aggregates and protecting active organic carbon fractions from rapid oxidation. In heavily degraded sryland systems, such as the arid zones of Nusa Tenggara, these carbon amendments must be strategically paired with advanced vegetative conservation techniques, including multi-strata agroforestry and permanent cover cropping using deep rooted legumes. These vegetative covers provide continuous structural shading that lowers soil surface temperatures, systematically reducing thermal mineralization rates of organic matter while mitigating kinetic erosion forces during intense tropical rainfall events. Futhermore, the adoption of conservation tillage (minimum or zero tillage) practices minimizes mechanical soil distrubance, preserving the structural intergrity of fungal hyphae networks and preventing the accelerated release of sequestered carbon dioxide into the atmosphere, thereby aligning domestic agricultural rehabilitation with global climate mitigation paradigms.

Beyond physically stabilizing soil aggregates through carbon amendments, structural restoration relies heavily on optimizing mirobiome driven biological processes. Restoring degraded tropical landscapes requires introducing site specific microbial inoculants, particularly native Arbuscular Mycorrhizal Fungi (AMF) and Plant Growth Promoting Rhizobacteria (PGPR), which accelerate nutrient solubilization networks. These biological inoculants colonize the rhizosphere, forming vast underground hyphal networks that effectively multiply the root surface area. This expansion allows crops to access deep subsoil water reserves and extract fixed phosphorus fractions that were previously chemically locked in acidic soils. However, field trials indicate that the survival and functional efficacy of these bio-inoculants depend heavily on the concurrent availability of strable organic substrates. Without a sufficient carbon matrix to serve as an energy source, introduced mirobial populations face rapid decline due to competition from native soil fauna. Therefore, modern agronomic frameworks must adopt a coordinated, dual system approach that delivers high stability carbon carriers alongside elite biological strains. This synchronized strategy ensures long-term microbial persistence, driving sustained bio-ghemical cycling necessary to support resilient, high yield food production systems.

3.4.2 Institutional frameworks and food diversification

At the policy level, national initiatives like the Critical Land Rehabilitation Acceleration (RHL) must transition toward community-based monitoring to resolve intersectoral coordination gaps. These rehabilitation programs should be paired with food diversification strategies. Promoting climate smart cultivation of local root crops and grains (e.g., sorghum, cassava, taro) reduces farming dependency on vulnerable, overexploited rice fields. FAO (2022) assessments indicate that climate smart agricultural frameworks can improve marginal land productivity by up to 20%.

3.4.3. Socio-economic resilience and rural livelihoods

Persistent soil degradation increases production costs and reduces profit margins, pushing smallholders into unsustainable farming cycles. Reports from BPN (2022) show that household in heavily degraded ecosystems register FSI scores 15% to 20% lower than those in fertile regions, which drives rural out-migration and reduces available agricultural labor. To counter this trend, national food strategies must provide accessible green financing and direct economic incentives for famers adopting conservation techniques. By treating soil health as a central performance metric within national resilience frameworks, Indonesia can protect its agricultural foundations, align with SGDs 2 and 15, and secure a more stable food system against future climate shocks.

Accelerating the widespread grass roots adoption of sustainable land management (SLM) practices requires overcoming the severe liquidity constraints faced by low income smallholder farming communities. Because sustainable soil restoration projects involve high upfront capital costs and extended payback periods, traditional commercial banking sectors frequently classify smallholders as high-risk borrowers, effectively locking them out of formal credit markets. To bridge this institutional financing gap, the state must orchestrate inclusive green financing frameworks, such as dedicated agricultural carbon credits, low interest ecological loans, and micro insurance programs designed to cushion seasonal transition risk. According to the socio-economic assessments by Olarewaju et al., (2025), providing targeted financial incentives directly to smallholders who actively practice crop diversification and erosion control significantly improves local compliance and long-term project viability. These innovative financial mechanisms must be seamlessly integrated with modern, digital agricultural extension platforms. Ultilizing mobile based applications and remote sensing data allows centralized extension services to deliver real time, province specific climate smart advisories, precision fertilizer formulations, and early warning degradation matrices directly to rural farmers. Bby combining accessible green capital with localized digital knowledge co-creation, national agricultural strategies can effectively empower smallholder farmers to transition from short-term survival tactics to active, long-term environmental stewardship, securing rural livelihoods against climate included supply chain disruptions.

The long-term viability of tech driven sustainable land management depends on establishing inclusive, community led monitoring frameworks. Top-down agricultural mandates historically failed to sustain local compliance because they disregarded co-managements models that empower smallholders as active citizen scientist. By training local farming cooperatives to use low cost visual soil assessment tools and open source mobile mapping applications, communities can track changes in topsoil quality and erosion control in real time. This grass roots data generation creates transparent feedback loops that allow local cooperatives to adjust conservation practices autonomously while providing verfied field data to regional agricultural extension offices. Shifting the smallholder's role from a passive policy recipient to an active steward of environmental data fosters deep institutional ownership. This inclusive approach builds social capital and strengthens the collective resilience of rural commuinities against larger macroeconomic and climate shocks.

3.4.4 Deeper theoretical synthesis and cross-country comparative policy analysis

To contextualize Indonesia's ongoing institutional struggle with soil degradation and food system vulnerability, useful parallel insights can be extracted from international policy frameworks executed in India, Vietnam, and Thailand. Each of these Asian agrarian economies present distinct models of balancing intensive agricultural production with ecological preservation farmeworks, offering valuables lessons for Indonesia's domestic strategy. In evaluating global standards, the Indian Model demonstrates that India's approach to the soil food security nexus provides an important case study regarding the scale of nationwide technological monitoring. Facing systemic nutrients depletion across its primary grain-producing regions due to decades of intensive Green Revolution practices, the Indian government launched the nationwide Soil Health Card (SHC) scheme. This policy initiative institutionalized micro-level soil testing, providing hundreds of millions of farmers with customized, data driven recommendations regarding precise fertilizer dosage and localized nutrient deficiencies. Theoretically, this intervention aims to decouple high agricultural yields from indiscriminate chemical over application. for Indonesia, the Indian experience underscores the absolute necessity of transitioning from generalized national agricultural guidelines to precision soil management frameworks that cater to localized provincial soil variations.

Meanwhile, In Vietnam, particularly within the hyper productive Mekong Delta, agricultural policy has increasingly centered on Climate Smart Agriculture (CSA) frameworks to combat severe soil salinization and shifting hydrological patterns. The Vietnamese state has actively promoted structural adaptions, such as the alternating rice shrimp farming model, which allows coastal farmers to dynamically utilize brackish waters during high salinity seasons instead of unsustainably forcing intensive rice monocultures. This model demonstrates high socio-ecological resilience by adapting to environmental constraints rather than fighting them. Indonesia, with its expansive but highly fragile peatlands and coastal agricultural zones, can derive immense value from Vietnam's targeted adaptation paradigm, emphasizing that food security does not require uniform crop expansion but rather localized ecological diversification.

Furthermore, in Thailand, its national soil conservation strategy offers a unique blend of institutionalized conservation technology and community driven socio-economic philosophies. Grounded heavily in the "Sufficiency Economy Philosophy", Thai agricultural policies emphasize long-term smallholder self-reliance through organic composting, vetiver grass cultivation for watershed erosion control, and strict limitations on chemical input dependencies. This framework treats soil health not merely as an isolated biochemical variable, but as the foundational asset of rural community resilience. By embedding soil conservation within a holistic socio-economic philosophy, Thailand has successfully forested high rates of local compliance and grass roots adoption among its farming populations. This highlights a critical policy lessons for Indonesia: technical soil mitigation strategies must be accompanied by culturally resonant, community led socio-economic frameworks to achieve long-term institutional sustainability across diverse provincial territories.

3.5 Theoretical and pratical implications for socio-ecological soil governance

The empirical findings and multi source institutional trangulations presented in this study offer profound theoretical nad practical contributions to the shifting discourse on agrarian sustainability in Southeast Asia. From a theoretical perspective, this research expands the traditional boundaries of environmental determinism by emberdding the soil food nexus firmly within soico-ecological resilience theory. Rather than viewing soil degradation merely as an isolated, linear biochemical phenomenon, our frameworks conceptualizes it as a dynamic socio-ecological feedback loop. Physical land degradation is actively driven by, and conversely exacerbates, systemic socio-economic vulnerabilities such as land tenure insecurity and uneven regional development. This critical positioning aligns with recent conceptual advancements by Poderati (2025), who argued that global soil security cannot be decoupled from local human security and institutional performance. Futhermore, our analysis of non soil cofounding variables contributes to macro regional scholarship by proving that regional market integration and local governance mechanismes can serve as vital shock absorbers, temporarily decoupling physical land degradation from immediate rural food insecurity. This macro-micro linkage supports the theoretical models proposed by Zhang, (2024), emphasizing that sustainable soil stewardship requires an explicit unerstanding of structural economic constraints operating at the smallholder level.

Practically, these findings serve as a strategic bluerpint for national policymakers, regional agricultural extension services, and environmental planning agencies in Indonesia. The localized provincial analysis demonstrates that uniform, top-down agricultural mandates are fundamentally inadequate due to the high ecological heterogenity across the Indonesian archipelago. For instance, the high chemical fertilizer depedency observed in intensive Javanese rice systems requires structural disincentives and a shift toward organic matter restoration. In contrast, the severe spatial erosion and acidity challenges in the outer islands require heaviliy subsidized lime applications and agroforestry interventions. Consequently, state agencies must transition toward decentralized, province-specific agricultural guidelines that integrate ecological data directly into regional spatial planning (Rencana Tata Ruang Wilayah). As highlighted by Loria & Lal (2025), integrating localized soil organic carbon metrics into national climate mitigation planning is the most cost effective strategy to achieve dual progress in both food security and global climate resilience goals. Ultimately, these practical interventions bridge the gap between abstract international mandates, such as SDG 2 and SGD 15, and tangible grass-roots agricultural execution.

4. Conclusions

This study demonstrates that soil degradation operates as a critical, systemic limiting factor that directly constrains Indonesia's national food security and compromises its agricultural carrying capacity. The integration of secondary macro data highlights as clear negative linear correlation between critical land distribution and regional Food Security Index (FSI) outcomes, specifically visible in highly degraded provinces outside Java, such as East Nusa Tenggara and West Kalimantan. Agronomically, continuous overexploitation and chemical imbalances such as the national NPK application ratio imbalance of 10:3:1 have triggered severe soil organic matter depletion, leading to stagnant crop yields despite expanding inputs. Consequently, transitioning national agricultural paradigms from purely production driven targets toward holistic, soil quality centric frameworks is essential to secure and adaptive, resilient food ecosystem that aligns with Sustainable Development Goals (SGDs) 2 and 15.

Despite the empirical insight, several limitations within this study must be acknowledged. Because this research is appropriately scoped as a secondary data analysis, the findings are constrained by a descriptive qualitative approach and do not include advanced econometric modeling, inferential statistics, or primary soil sampling datasets. Furthermore, while cross provincial comparisons reveal strong trends, the macro level nature of the utilized institutional datasets limits the ability to isolate specific local level confounding variables, such as household scale poverty dynamics and variations in micro governance capacity, which could also influence regional food security outcomes.

To address these limitations, future research directions should focus in migrating from descriptive syntheses to more advanced methodology extensions. Future studies are highly encouraged to implement GIS based spatial modeling and longitudinal remote sensing monitoring to map the real time degradation of active agricultural soils. Additionally, integrating primary household farming surveys will allow future researchers to quantify the micro economic impacts of soil fertility loss on smallholder income stability. Ultimately, expanding these empirical dimensions will provide the precise, data driven insights necessary to integrate soil conservation metrics into national level resilience planning and sector specific policies.

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Author Contribution

All contributions to the conception, design, data analysis, interpretation, and manuscript preparation were carried out by the author. The author has read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

In this study, the researchers honestly acknowledge the use of Generative AI tools, specifically ChatGPT, solely to assist with academic language editing and to improve sentence clarity before the manuscript was finalized. All content, analysis, interpretation, and conclusions presented in this research were fully developed by the authors, who take full responsibility for the manuscript.

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