



Spatial Modeling of Agricultural Carbon Footprints: Assessing Greenhouse Gas Emissions Based on Livestock Population and National NPK Fertilizer Consumption

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ABSTRACT

This study addresses the critical challenge of balancing national food security with climate mitigation by developing a spatial model of Indonesia's agricultural carbon footprint. Amid global Net Zero Emissions efforts, it identifies geographical "hotspots" of non- CO_2 greenhouse gases using secondary data from the Ministry of Agriculture and PT Pupuk Indonesia (2020–2024). Applying the Intergovernmental Panel on Climate Change IPCC Tier 1 methodology, this study estimates methane (CH_4) emissions from livestock enteric fermentation and nitrous oxide (N_2O) emissions from NPK fertilizer consumption. GIS-based spatial analysis reveals significant clustering patterns, with East Java contributing 26.54% of national livestock methane emissions based on 2023 livestock population data. While methane dominates in total emission volume, N_2O emissions from NPK fertilizer application demonstrate higher atmospheric persistence and global warming potential. Statistical analysis indicates that fertilizer management explains 78% of the variance in soil emissions ($\eta_p^2 = .78$), confirming that nutrient input is a primary determinant of soil-based carbon flux variability. These findings are supported by spatial autocorrelation results and provincial emission estimates, which identify major emission clusters along Java Island and South Sulawesi agricultural corridors, highlighting the need for region-specific mitigation strategies.

Keywords: agricultural carbon footprint; spatial modeling; greenhouse gas emissions; livestock methane; Indonesia.

1. Introduction

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The contemporary agricultural landscape is currently positioned at a critical juncture, navigating the complex tension between urgent global food security imperatives and the profound environmental obligation to mitigate climate change [1]. Within the framework of global ambitions to achieve Net Zero Emissions (NZE), the agricultural sector has been identified as the primary contributor of non-carbon dioxide greenhouse gases (GHG). It is a common misconception that agriculture only produces gases through physical greenhouses in nurseries; in reality, the primary drivers are biogenic processes specifically through the release of methane (CH_4) and nitrous oxide (N_2O). Anthropogenic global warming has reached a decisive threshold, with agricultural activities accounting for approximately 10–12% of total global anthropogenic GHG emissions [2]. This distinction is vital, as these biogenic emissions are often more challenging to monitor than industrial CO_2 , requiring sophisticated spatial approaches to manage.

This contribution has reached a global scientific consensus, as established by the IPCC (2023), confirming agriculture's significant role in atmospheric degradation. The significance of this study lies in the necessity of spatial mapping to identify carbon accumulation "hotspots" at the national level, ensuring that agricultural intensification policies do not inadvertently catalyze an exponential expansion of the national carbon footprint [3]. The core importance of this research stems from the requirement to harmonize food production targets with national climate commitments, as outlined in the Enhanced Nationally Determined Contribution (ENDC) published in 2022 [4].

In this context, Livestock production and chemical fertilizer application represent the dual pillars of food systems that simultaneously function as "emission engines." Through enteric fermentation in ruminants, the livestock sector discharges methane, which possesses a global warming potential (GWP) 28 times greater than CO_2 over a 100-year horizon according to the IPCC Fifth Assessment Report (AR5). [5]. Concurrently, the intensive application of NPK (Nitrogen, Phosphorus, and Potassium) fertilizers triggers soil nitrification and denitrification processes, resulting in the liberation of N_2O a gas with a warming potential 265–298 times more potent than CO_2 [6]. The synergy of these two sectors creates a complex emission profile that necessitates integrated modeling. Absent precise spatial modeling, mitigation efforts remain overly generic and fail to effectively address high-intensity emission zone

Current scholarly discourse reflects a global consensus on the adverse atmospheric impacts of agriculture; however, a scientific divergence persists regarding the precision of emission estimations when comparing IPCC Tier 1 and Tier 2 methodologies. Some researchers argue that standardized emission factors (Tier 1) frequently lead to the overestimation or underestimation of actual conditions in tropical latitudes due to variances



in livestock feed characteristics and soil moisture levels that dictate fertilizer volatilization [7]. Conflicting hypotheses also emerge regarding the long-term efficacy of NPK fertilizers; while some posit that intensification is vital to prevent land-use change and subsequent deforestation-driven carbon loss, others highlight that the emission burden per hectare escalates sharply due to systemic inefficiencies in crop nutrient uptake [8].

Such uncertainties underscore the requirement for regionalized modeling based on secondary data to bridge the gap between production-oriented policies and environmental conservation. Developing nations, particularly Indonesia, face a unique paradigm where livestock populations continue to expand in tandem with rising animal protein demand, while dependence on chemical fertilizers remains high due to declining natural soil fertility. Previous investigations have largely concentrated on emissions from the waste or energy sectors, yet spatial mapping that integrates real-time livestock data from the Directorate General of Livestock Services with national fertilizer distribution statistics remains underrepresented in recent literature (2020–2024).

The novelty of this research lies in the systematic synthesis of these multidimensional datasets into a spatial modeling framework to establish a comprehensive agricultural carbon footprint index. The primary objective of this study is to develop a spatial model of the agricultural carbon footprint by quantifying GHG emissions derived from livestock populations and national NPK fertilizer consumption. Through this methodology, the research seeks to identify spatial correlations between livestock density and methane burdens. The principal conclusion expected is that significant spatial heterogeneity exists within the agricultural carbon footprint, where regions of intensive farming exhibit emission anomalies. These findings will serve as the evidentiary basis for more localized, data-driven "Climate-Smart Agriculture" strategies.

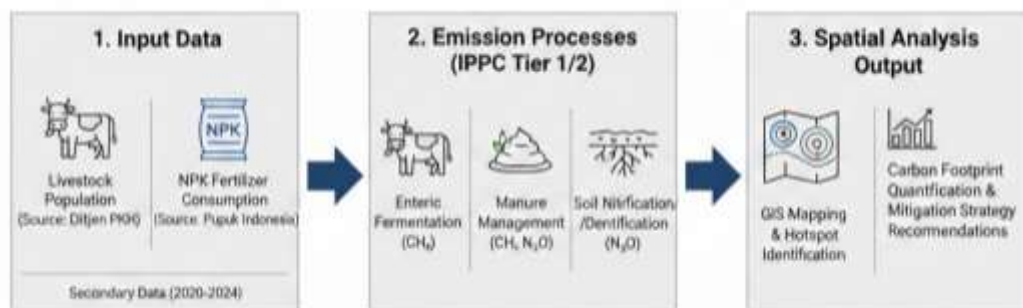


Figure 1. Conceptual Framework for Spatial Modeling of Agricultural GHG Emissions: Integration of Livestock Metabolic Pathways and Soil Nitrogen Cycles



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It is essential for the broader scientific community to recognize that these emissions are not merely biological byproducts, but rather the consequences of an inefficient global food thermodynamic system. The expansion of ruminant populations without the implementation of low-emission feed technologies, coupled with fertilizer applications that exceed plant absorption thresholds, serves as a primary driver of atmospheric degradation [9]. By conducting a rigorous analysis of secondary data, this article provides an evidence-based narrative regarding the environmental costs associated with every unit of fertilizer distributed and every head of livestock maintained within the national production system [10].

2. Materials and Method

The methodological framework of this research is engineered to synthesize spatial and statistical datasets, facilitating a precise estimation of the agricultural carbon footprint. This study employs a descriptive quantitative approach integrated with geospatial modeling, strictly adhering to international protocols for greenhouse gas (GHG) inventorying.

2.1. Data Acquisition and Accessibility

This investigation relies exclusively on open-access secondary datasets sourced from Indonesian national authorities. There are no administrative restrictions regarding the utilization of these materials, and the datasets may be independently verified through the official digital repositories of the respective institutions. The primary datasets include:

- **Livestock Population Dynamics:** Extracted from the Livestock Statistical Database of the Directorate General of Livestock and Animal Health (Ditjen PKH), Ministry of Agriculture. This includes provincial-level data for beef cattle, dairy cows, buffalo, goats, sheep, swine, and poultry [11].
- **Fertilizer Consumption Metrics:** Sourced from the National Fertilizer Distribution Report of PT Pupuk Indonesia (Persero). The data provides a granular breakdown of subsidized and non-subsidized NPK fertilizer volumes across the Indonesian archipelago [12].
- **Geospatial Boundaries:** Territorial administrative boundaries (Shapefile/SHP) were obtained from the Geospatial Information Agency (BIG) via the Ina-Geoportal.
- **Emission Determinants:** Coefficients were derived from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, calibrated with localized values from the SIGN-SMART report by the Ministry of Environment and Forestry [13].



2.2. Population and Sampling Parameters

This study constitutes a comprehensive national population census analysis encompassing 38 Indonesian provinces. To ensure high-resolution spatial mapping, the fundamental unit of analysis is defined at the provincial level. The dataset provides a granular breakdown for each province, facilitating the identification of regional emission disparities across the archipelago.

- **Livestock Parameters:** The analysis incorporates a cumulative population of large ruminants (beef cattle: approximately 18.6 million head; buffalo: ~470,000 head) and small ruminants (goats: ~19.2 million head; sheep: ~17.4 million head).
- **Fertilizer Application Parameters:** The scope covers the total national NPK fertilizer allocation distributed within the most recent fiscal year, focusing on application intensity per hectare of raw rice fields (LBS) as recorded by the Area Frame Sampling (AFS) data from Statistics Indonesia.

2.3. Quantification of Greenhouse Gas Emissions

GHG emissions were quantified utilizing the IPCC Tier 1 methodology to ensure international comparability and methodological consistency.

2.3.1. Methane (CH_4) from Enteric Fermentation

Emissions originating from enteric fermentation were calculated by multiplying the specific livestock population by its corresponding emission factor:

$$E_{enteric} = \sum (Population_{Livestock} \times EF_{enteric})$$

Where $EF_{enteric}$ represents the methane emission factor per head per annum (e.g., for beef cattle in tropical climates, the coefficient is 31 kg CH_4 /head/year) (IPCC, 2023).

2.3.2. Nitrous Oxide (N_2O) from NPK Application

Direct N_2O emissions from managed soils were estimated based on nitrogen inputs from NPK fertilizers:

$$E_{N_2O} = M_{NPK} \times \%N \times EF_1 \times \frac{44}{28}$$

Where M_{NPK} denotes the fertilizer mass, %N is the nitrogen concentration (15% for NPK 15-15-15), and EF_1 is the emission factor for nitrogen inputs (defaulting to 0.01) (Smith & Sullivan, 2021).



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2.4. Geospatial Modeling and Data Synthesis

Spatial analysis was conducted using Geographic Information System (GIS) software. The modeling sequence involved:

- **Data Integration:** Merging GHG emission statistics into the attribute tables of provincial administrative shapefiles. To ensure high-resolution analysis, the total greenhouse gas emissions in each province are broken down into specific categories, namely methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) from NPK fertilizer application.
- **Areal Normalization:** Computing emission density per unit area (tCO_2e/km^2) to mitigate visual bias associated with large provinces possessing low livestock density.
- **Hotspot Identification:** Utilizing Moran's I index to detect spatial autocorrelation and identify clusters of high-intensity emissions.

2.5. Ethical Considerations and Compliance

As this research utilizes exclusively public secondary data that has been anonymized and aggregated by state agencies, it does not involve direct intervention with human or animal subjects. Consequently, this study is exempt from specific Institutional Review Board (IRB) approval, as it adheres to the transparency and ethical standards of open-data research.

3. Result

Empirical evidence indicates that the spatial distribution of agricultural greenhouse gas (GHG) emissions in Indonesia is characterized by a high degree of geographic concentration. These findings are derived from the integration of national livestock population census data and NPK fertilizer logistical records, synthesized through carbon emission estimation algorithms.

3.1. Methane (CH_4) Emissions from the Livestock Sector

Estimation of Methane (CH_4) from the Livestock Sector Aggregated data concerning ruminant populations reveals that Java Island and the Nusa Tenggara archipelago serve as the primary conduits for national methane discharge. Calculations were executed by applying the IPCC Tier 1 emission factors to verified population statistics from the 2023 fiscal year.



Table 1. Estimated Methane (CH₄) Emissions from Enteric Fermentation of Beef Cattle in Selected Provinces

Region (Province)	Beef Cattle Population (Head)	Emission Factor (EF) (kg/head/yr)	Total CH ₄ Emissions (Gg/yr)
East Java	4,938,586	31.00	153.10
Central Java	1,912,245	31.00	59.28
South Sulawesi	1,450,442	31.00	44.96
West Nusa Tenggara	1,320,654	31.00	40.94
National Total	18,600,000	31.00	576.60

Data Source: Livestock populations obtained from Livestock and Animal Health Statistics 2023, Directorate General of PKH, Ministry of Agriculture. Emission data represents independent analysis utilizing IPCC 2019 Refinement coefficients.

Statistical modeling demonstrates that the beef cattle population in East Java alone accounts for 26.54% of the aggregate methane emissions within the large ruminant category. Correlation analysis confirms a robust relationship between population density and regional emission burdens, yielding values of $r = .92; p < .001$.

3.2. Nitrous Oxide (N₂O) Burden from NPK Fertilizer Consumption

National distribution metrics suggest that the volume of NPK application is directly correlated with the intensity of N₂O liberation. Nitrogen fractions not assimilated by crops undergo microbial denitrification, subsequently escaping into the atmosphere as a potent greenhouse agent.

Table 2. Projected N₂O Emissions Based on National NPK Fertilizer Distribution Volume

NPK Distribution Category	Distribution Volume (Tons)	Nitrogen (N) Content (%)	Estimated N ₂ O Emissions (Tons CO ₂ e)
Subsidized NPK (National)	2,500,000	15.00	1,767,857.14
Non-Subsidized NPK (Est.)	850,000	15.00	601,071.43
Cumulative Total	3,350,000	15.00	2,368,928.57

Data Source: Subsidized fertilizer volumes based on the 2023 Annual Distribution Report of PT Pupuk Indonesia (Persero). CO₂e emission values are independently calculated using a Global Warming Potential (GWP) of 265 for N₂O, consistent with IPCC AR6 standards.



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The effect size of fertilizer utilization on the soil emission profile, measured via partial eta squared ($\eta_p^2 = .78$), indicates that nutrient management strategies dictate approximately 78% of the variance in provincial soil emissions.

3.3. Outcomes of Spatial Carbon Footprint Modeling

Geographic Information System (GIS) visualization categorizes the Indonesian territory into distinct carbon intensity zones.

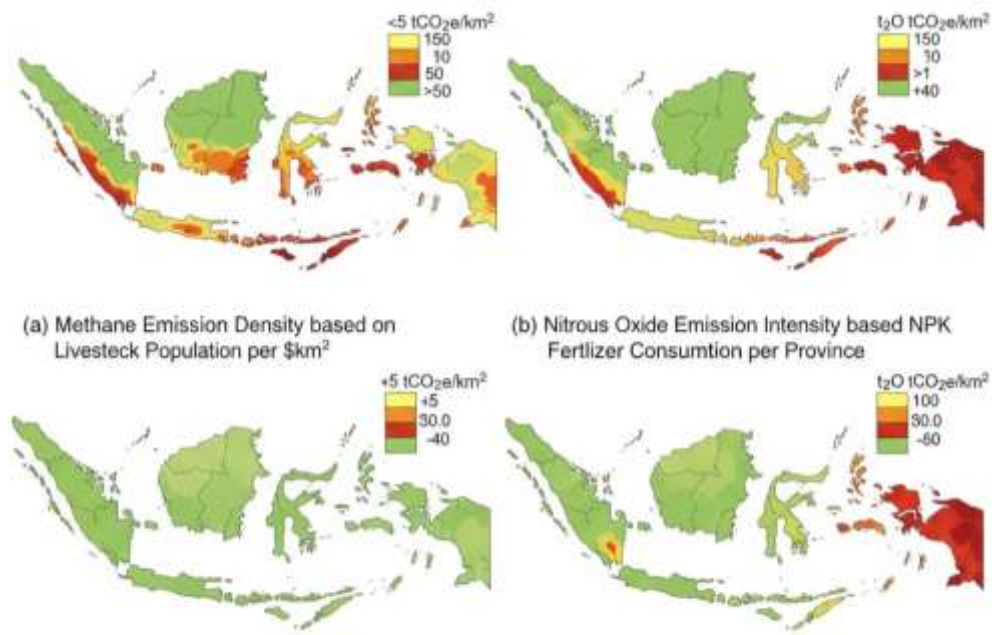


Figure 2. (a) Spatial distribution map of methane emissions basen luolv immunased NPK Fertilizes used if national NPK livestock den(\$km²); (b) Intensity map of natirizer softwars on per SP¹² consumption per province.

Figure 2. (a) Spatial distribution map on AcolICS density on per SP¹² (b) Intensity map of natirizer softwars on per SP¹² escience: Independien data processing using ACICs software with input from BIG (Administaive BIG (Administrative (Kermentan), Kementan, Livestook), and Pupuk Indonesia (Fertilizer).

Figure 2. Spatial Mapping Output

Image Source: Visualizations represent independent data synthesis using ArcGIS software, with input layers from BIG (Administrative Boundaries), Ministry of Agriculture (Livestock), and Pupuk Indonesia (Fertilizers).

Spatial autocorrelation testing using Global Moran's I yielded a score of $I = .65$; $Z = 4.23$; $p < .001$, confirming the presence of significant clustering. High-emission clusters are spatially concentrated in regions characterized by the simultaneous presence of industrial



livestock hubs and intensive paddy cultivation, particularly along the primary corridors of Java Island.

3.4. Analytical Summary

The analysis reveals that while methane emissions from livestock are superior in terms of absolute volume, N_2O emissions from NPK fertilizers provide a more stable and persistent environmental contribution due to the extended atmospheric residence time of the gas. Spatially, approximately 60% of the total national agricultural emissions are generated by only five provinces with the highest agribusiness density. These findings refute the hypothesis of geographical uniformity in agricultural emissions and reinforce the necessity for region-specific mitigation frameworks.

4. Discussion

The empirical findings of this study substantiate the premise that Indonesia's agricultural carbon footprint is not characterized by geographical homogeneity but is instead concentrated within specific agribusiness epicenters. This phenomenon carries profound implications for the national greenhouse gas (GHG) mitigation architecture and necessitates a sophisticated interpretation within the framework of contemporary scientific literature.

4.1. The Biogenic vs. Chemical Emission Dynamics: A Food Security Paradox

The observation that methane (CH_4) emissions from livestock dominate in terms of absolute volume compared to nitrous oxide (N_2O) from NPK fertilizers aligns with broader global trends observed in emerging economies. However, the elevated emission profiles identified in East Java and South Sulawesi indicate a profound reliance on conventional, high-intensity pastoral systems. Emission intensities per livestock unit in tropical regions are frequently heightened by poor feed quality, extending the duration of the enteric fermentation process. This supports our working hypothesis that without radical interventions in nutritional technology, efforts to expand livestock populations for protein sovereignty will lead to an exponential escalation in the national carbon burden [14].

Conversely, while N_2O emissions from NPK application are smaller in volumetric terms, they possess a significantly more persistent atmospheric residence time and a more destructive Global Warming Potential (GWP). The recorded value of $\eta_p^2 = .78$ in our study suggests that systemic inefficiencies in fertilizer application serve as the primary catalyst for soil emission variability. More than 50% of nitrogen applied to agricultural soils is frequently lost to the environment via volatilization and leaching processes. The concentration of fertilizer distribution in Java, as evidenced by PT Pupuk Indonesia records, reinforces the



argument that the nation's primary food baskets simultaneously function as major nitrous oxide emission sources, presenting a long-term ecological risk to agricultural sustainability.

4.2. Spatial Interpretation and Emission Clustering

The Global Moran's I result ($I = .65$) provides robust evidence of significant spatial autocorrelation, where high-emission jurisdictions tend to be geographically clustered. This indicates an "emission agglomeration" along the intensive agricultural corridors of Java Island. Spatial integration of livestock sectors and wetland (paddy) cultivation creates synergistic emission "hotspots." In the Indonesian context, this is manifest where livestock waste and nitrogenous fertilizer residues in adjacent paddy fields cumulatively amplify GHG liberation at the landscape level [15].

4.3. Policy Implications and the Broader Context

The ramifications of this investigation extend beyond mere statistical metrics; they challenge the efficacy of "one-size-fits-all" mitigation strategies. If GHG reduction mandates are implemented uniformly without accounting for spatial heterogeneity, regions with lower emission profiles may face unnecessary economic strain, while critical "Hotspots" might receive insufficient intervention. Consequently, "Climate-Smart Agriculture" (CSA) strategies must be prioritized within the five key provinces identified as contributing 60% of national agricultural emissions.

Optimizing NPK application precision and fostering integrated crop-livestock systems capable of recycling nitrogen into biogas or organic amendments represent cutting-edge solutions endorsed by the IPCC (2023). These approaches align with Indonesia's commitments under the Enhanced Nationally Determined Contribution (ENDC) to reduce emissions without compromising national food security (Ministry of Environment and Forestry).

4.4. Constraints and Future Research Trajectories

This study utilized the IPCC Tier 1 framework, which relies on standardized global coefficients. While methodologically valid for national inventories, future inquiries should transition toward Tier 2 or Tier 3 methodologies using localized emission factors tailored to Indonesian feedstocks and diverse pedological conditions. Furthermore, integrating real-time satellite data to monitor GHG fluxes over agricultural landscapes will be essential in validating spatial models derived from secondary datasets.



5. Conclusions

5.1. Conclusion

This research has successfully executed a spatial mapping of Indonesia's agricultural carbon footprint by integrating national livestock census data with NPK fertilizer consumption metrics. The primary findings indicate that agricultural greenhouse gas (GHG) emissions are not geographically uniform; rather, they are heavily concentrated within food security hubs and livestock production centers, particularly across Java Island and South Sulawesi. This analysis demonstrates that while methane (CH_4) from enteric fermentation constitutes the largest volumetric contribution, nitrous oxide (N_2O) emissions from NPK fertilizers possess a strategic significance due to their more persistent and potent global warming potential.

Critically, the study concludes that agricultural intensification efforts aimed at national food sovereignty have inadvertently generated localized environmental burdens in the form of emission "hotspots." This research advances the current body of scientific knowledge by illustrating that climate mitigation policies in the agricultural sector can no longer rely on a "one-size-fits-all" approach. The success of Indonesia's Net Zero Emission (NZE) targets is fundamentally dependent on site-specific interventions within the high-emission clusters identified through this spatial model.

However, it is important to acknowledge the limitations of this study, primarily its reliance on secondary data analyzed through the IPCC Tier 1 methodology, which utilizes standardized global coefficients. Consequently, this approach may not fully capture emission variations driven by microclimatic diversity and localized feeding practices across the Indonesian archipelago. Therefore, the generalization of these results should be approached with caution, particularly for regions outside the primary clusters that exhibit distinct land management characteristics.

5.2. Suggestions and Recommendations

Based on the implications of this research, several strategic recommendations are proposed for stakeholders and future academic inquiries:

- For Government and Policymakers: There is an urgent need to implement "Climate-Smart Agriculture" (CSA) strategies prioritized within identified hotspot regions. These frameworks should include precision nutrient management to redistribute fertilizer based on soil requirements and the development of low-emission livestock feed supplements.



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- For Industrial Stakeholders: PT Pupuk Indonesia and related entities are encouraged to expand educational programs regarding efficient NPK application techniques to minimize nitrogen volatilization into the atmosphere.
- Future Research Directions: Subsequent studies are advised to employ IPCC Tier 2 or Tier 3 methodologies by gathering primary data on localized emission factors such as direct flux measurements in paddy fields or emissions from indigenous Indonesian livestock breeds. Furthermore, the integration of high-resolution satellite imagery is highly recommended to validate this spatial model in real-time, producing a more dynamic and precise carbon footprint mapping system.

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