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Research article

Assessing the drivers of nitrogen fertilizer application in Panama to support sustainable nutrient management

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ABSTRACT

Nitrogen fertilizers are vital for global food production, but their overuse can degrade ecosystems and compromise agricultural productivity. Although fertilizer use is increasing in Latin America, research on the drivers of nitrogen application remains limited, particularly at subnational scales where management decisions are made. Using the Republic of Panama as a model system, this study integrates census data, government records, Landsat imagery, and interviews with farmers to identify the factors shaping nitrogen application across districts. Nitrogen inputs varied widely among crops, with bananas and pineapples exhibiting the highest mean application rates at 278 and 189 kg ha^{-1} yr^{-1}, while coffee, oranges, and pigeon pea received far lower amounts (<40 kg ha^{-1} yr^{-1}). Agronomic factors were particularly influential, and both crop type and farm size emerged as significant predictors of nitrogen use. Notable, larger farms applied more nitrogen per hectare, as indicated by the positive elasticity of farm size where a 1 % increase in farm size corresponded to a 0.35 % increase in nitrogen application, likely reflecting greater resource availability and the use of more input-intensive production systems. In contrast, districts with greater adoption of conservation practices applied less nitrogen overall, underscoring the role of sustainable management in reducing fertilizer inputs. For example, model predictions indicate that increasing conservation adoption from 15 % to 25 % at the district level is associated with a 39 % reduction in nitrogen application. We also generated the first district-level nitrogen fertilizer application map for Panama, revealing substantial spatial variation ranging from 10.34 to 1032.60 kg ha^{-1} yr^{-1}, with central and western districts showing the highest values. These findings underscore the complexity of fertilizer use across Panama and emphasize the need to consider farm structure, crop composition, and conservation practices when designing strategies for sustainable nutrient management, providing an essential baseline for future policy and decision making.

1. Introduction

Population growth places significant pressure on the demand for food and energy resources produced by industries such as agriculture (Foley et al., 2011). To meet these demands, nitrogen (N), a vital nutrient for plant growth and development, plays a pivotal role as a key component of commonly used fertilizers in agriculture (Zhang et al., 2015). Since the early 20th century, the industrial fixation of nitrogen through the Haber-Bosch process, which converts atmospheric dinitrogen (N_2) into ammonia (NH_3), has expanded the nitrogen fertilizer industry (Galloway et al., 2021). This technological advancement has not only driven substantial increases in crop yields but has also enabled the widespread intensification of agricultural systems worldwide, transforming global food production. As nitrogen fertilizers became more accessible and widely used, they have become indispensable for maintaining high agricultural productivity and addressing food security challenges. This central role in food systems has positioned nitrogen as a key element in advancing the United Nations Sustainable Development Goals (SDG), particularly SDG 2, which aims to end hunger and promote sustainable agriculture (Economic Commission for Latin America and the Caribbean [ECLAC], n.d.).

Although nitrogen is essential for meeting global food demands, its excessive application in agriculture can undermine productivity and threaten ecosystem health (Bodirsky et al., 2014). In cereal crops such as wheat and rice, for instance, surplus nitrogen promotes leaf and stem growth at the expense of grain development, resulting in lower grain

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protein content and quality (Mondal et al., 2023). Over-fertilization with nitrogen also alters plant structure, decreasing resistance to pests and diseases (Tripathi et al., 2022). In terms of environmental effects, nitrogen runoff increases nitrogen concentrations in inland and coastal waters (Berger et al., 2022; Lee et al., 2019; Sheikholeslami and Hall, 2023), which promotes algal growth that leads to eutrophication, lowers dissolved oxygen levels, and reduces species diversity and ecological functions in coastal ecosystems (Diaz and Rosenberg, 2008). Furthermore, nitrogen-enriched soils promote the emissions of nitrous oxide (N_2O), a potent greenhouse gas that contributes to rising global temperatures (de Vries, 2021; Mao et al., 2021). Given these agricultural and environmental consequences, identifying best nitrogen management practices is therefore crucial for maintaining the crop yields while minimizing environmental impacts (Liu et al., 2016).

To develop more effective nitrogen management practices, the first step is to understand the factors that influence nitrogen application in agriculture (Hamid et al., 2021), particularly at subnational levels where interventions are implemented. This level of finer detailed information is often required in agriculture, as national-level statistics, while informative, frequently obscure critical variation in how nitrogen is applied across different farming systems and environmental conditions. Notably, this lack of spatially detailed information is common in many countries and is a growing concern in regions of the Global South, such as Latin America, where fertilizer use has risen significantly in recent decades and is projected to continue increasing (Galloway et al., 2021). Mid-term projections for the 2024–2028 period indicate that Latin America will become the second-largest contributor to global nitrogen-based fertilizer consumption, accounting for 23 %, just behind South Asia at 24 % (International Fertilizer Association, 2024). Moreover, long-term projections of global fertilizer consumption from 2020 to 2100—under different Shared Socioeconomic Pathway (SSP) scenarios—suggest that nitrogen consumption hotspots may shift from China to Latin America and the Caribbean (Gao et al., 2024), potentially driven by agricultural expansion and changing socioeconomic dynamics. Considering these scenarios, without a clear understanding of the underlying drivers of nitrogen application, it remains challenging to design targeted, site-specific strategies that enhance nitrogen input efficiency while reducing both present and future environmental impacts in the countries of the Latin American region.

This rising demand, however, is occurring in a context where most countries in the Latin America region rely heavily on imported nitrogen fertilizers, leaving them highly exposed to price increases and with limited control over fertilizer availability. For example, global market disruptions following the Russia–Ukraine conflict and pandemic-related demand pressures not only reduced the availability of fertilizers but also led to a 137 % increase in the value of fertilizer imports in Latin America in 2022 (IICA, 2022). This resulted in countries such as Panama experiencing the highest cost surge in the region, with fertilizer import values increasing by 155 % despite a 29.5 % reduction in import volumes, placing considerable financial pressure on its agricultural sector and national economy. Again, understanding the drivers of nitrogen application at finer spatial scales is therefore essential, not only to improve input efficiency and minimize impacts in the environment, but also because more efficient fertilizer use can help reduce reliance on imports and increase resilience in countries most affected by market fluctuations, such as Panama.

Panama's agricultural sector has undergone structural expansion in recent years, with the number of agricultural operations increasing by 10.28 % (INEC, 2025). This growth has been accompanied by the introduction of more diverse crops and the adoption of technologies aimed at improving productivity, such as mechanized planting and improved seed varieties. However, this expansion has not been uniform across the country. Provinces such as Chiriquí and Veraguas account for a large share of total agricultural operations, while Darién and Colón represent only a small fraction, reflecting strong environmental and socioeconomic gradients that likely influence fertilizer use (INEC, 2025). Despite this heterogeneity, the factors shaping nitrogen application in Panama, and more broadly across Latin America, remain poorly quantified. Regional research has primarily emphasized national fertilizer consumption trends, while far fewer studies investigate why farmers apply fertilizers the way they do or how local socioeconomic constraints and institutional conditions influence fertilizer decisions (e.g., González, 2014; Vasco et al., 2021; Vicente and Calle, 2024). As a result, subnational analyses capable of identifying the drivers of nitrogen application are rare, leaving major gaps in understanding fertilizer use across diverse tropical agricultural systems. Addressing this gap is essential for designing more efficient and context-specific nitrogen management strategies.

To better understand the drivers of nitrogen application, this study uses Panama as a model system and examines the influence of socioeconomic, agronomic, demographic, environmental, and conservation factors on fertilizer use at the district level. To do so, we conducted interviews with farmers across multiple regions to gather first-hand insights into fertilizer practices and the local conditions influencing their decisions. These findings were then integrated with data from agricultural census records, government statistics, environmental datasets, and Landsat satellite imagery. This integrative approach allowed us to identify the most influential factors shaping nitrogen application patterns across districts in Panama. We hypothesize that nitrogen application rates are primarily driven by agronomic and socioeconomic intensification, particularly larger cultivated areas, greater commercial orientation, and improved access to inputs, while conservation practices act as moderating forces that reduce fertilizer use across districts. Furthermore, using the best-performing predictive model from our analysis, we developed the first district-level map of nitrogen application in the country. This spatial representation captures regional variation and highlights areas with disproportionately high nitrogen input levels. Such patterns help identify regions at greater risk of environmental impacts and offer critical guidance for more targeted and effective policy measurement.

By identifying the key drivers that shape nitrogen use and producing the first spatially detailed nitrogen map for the country, our study provides information needed to support more efficient and environmentally sustainable nitrogen management. Although our research focuses on Panama, the approach and insights are broadly relevant to tropical agricultural systems across Latin America, where fertilizer use is rapidly intensifying (Austin et al., 2013), most of the countries in the region imports its fertilizers (IICA, 2022) and where similar socioeconomic and environmental pressures persist across the region (Cunha-Zeri and Ometto, 2021; Ometto et al., 2020). Panama represents a valuable model for examining the regional nitrogen challenge identified across Latin America (Cunha-Zeri and Ometto, 2021; Martinelli et al., 2006), which is characterized by persistent imbalances in fertilizer access and use (Martinelli et al., 2006; Ometto et al., 2020). Across Latin America, some agricultural areas rely heavily on nitrogen to sustain production, while others face chronic nutrient limitations linked to financial constraints, limited technical support and unequal access to key agricultural inputs (Austin et al., 2013; Cunha-Zeri and Ometto, 2021; Martinelli et al., 2006). These conditions reflect deeper inequalities in land use, market integration and agricultural investment. Panama's agricultural landscape, characterized by export-oriented production systems, traditional smallholder farming, and diverse environmental settings, closely mirrors these broader regional dynamics. This situation is further reinforced by limited institutional coordination on fertilizer management and fragmented nutrient governance, structural challenges widely documented across Latin America (Austin et al., 2013; Ometto et al., 2020). Taken together, these characteristics position Panama as a strong case study for examining the factors that influence nitrogen fertilizer use and for producing insights that can inform nutrient management in other tropical agricultural regions.

2. Material and methods

2.1. Study site

We conducted this study in Panama, a Central American country located in the intertropical zone. The country covers approximately 75,000 km^2 and functions as a land bridge between North and South America. It borders Colombia to the east and Costa Rica to the west, while the Caribbean Sea lies to the north and the Pacific Ocean to the south (The World Bank Group, 2024). Elevations range from sea level to about 3475 m at the highest point (Palka, 2005). Panama maintains a warm, humid climate throughout the year. Annual rainfall ranges from approximately 1600 to 3000 mm, with moisture-rich trade winds delivering the highest precipitation to the Caribbean region, while the Pacific side remains relatively drier (Palka, 2005). The country experiences two distinct seasons: a dry season from December to April and a wet season from May to November. Recent analysis of climate data from 1991 to 2020 shows that the average annual temperature is 25.6 °C, with maximum mean temperatures ranging between 27.89 °C and 30.34 °C, and minimum temperatures between 21.79 °C and 22.86 °C (The World Bank Group, 2024). This combination of climatic and topographic factors supports the diverse ecosystems, and agricultural activities.

2.2. Brief description of the agriculture in Panama

While Panama's agricultural sector is considered diverse, with more than 35 types of crops cultivated across the country, the majority of production remains concentrated in a few key crops (MIDA, 2023). Staple grains such as rice, corn, and beans dominate the national agricultural landscape. For example, in the 2022/2023 marketing year, these grains collectively accounted for nearly 59 % (119,302 ha) of the total cultivated area (203,476 ha) (MIDA, 2023). Among them, rice is the most extensively grown, occupying 43 % (88,686 ha) of the cultivated land and yielding approximately 398,000 metric tons, making Panama the second-largest rice producer in Central America (USDA, 2023). Nevertheless, domestic production continues to fall short of national demand, requiring imports to meet consumption needs.

In addition to grain production, fruit plantations represent approximately 8 % of the total cultivated area of the country. Major fruit crops include musaceae such as plantain (10,975 ha), bromeliads like pineapple (1744 ha), and citrus fruits such as oranges (1411 ha) (MIDA, 2023). These crops play a dual role in meeting local dietary needs and contributing to the country's agricultural export economy. Among these main fruits crops, bananas stand out as a key export product. In 2023, Panama exported approximately $273 million worth of bananas, ranking as the 13th largest banana exporter globally out of 163 countries (Observatory of Economic Complexity, 2023). The same year, bananas also ranked as Panama's fifth most exported product out of a total of 1046 export categories (Observatory of Economic Complexity, 2023). This balance between domestic food security and export-oriented production highlights the strategic importance of a few high-impact crops in sustaining Panama's agricultural economy.

Although the agricultural sector currently contributes only 2.5 % to Panama's gross domestic product (World Bank, 2023), in terms of farming activity, it has experienced significant expansion in recent years. From 2011 to 2024, the number of registered agricultural producers increased from 245,100 to 266,712, while agricultural operations rose from 248,560 to 274,107 (Contraloría General de la República de Panamá, 2024). This expansion of agricultural activity is likely driven by the adoption of more diverse crops and the implementation of new technologies, including mechanized planting and improved seed varieties, which have helped increase productivity. Moreover, the distribution of agricultural operations varies considerably across the country. Provinces such as Darién and Colón account for only about 3 % and 5 % of total operations, respectively, while regions like Chiriquí and Veraguas hold 14 % and 15 % (INEC, 2025). These differences perhaps reflect the country 's varied environmental and socio economic conditions. While the sector continues to grow, it also presents environmental concerns, including deforestation, soil degradation, and nitrogen runoff, emphasizing the need for sustainable land management practices.

2.3. Data collection

2.3.1. Nitrogen application data

To assess nitrogen application in Panamanian agriculture, we conducted semi-structured interviews with farmers across the country, without pre-selecting participants based on crop type. This design allowed us to capture a broad range of nitrogen management practices across diverse farming systems and production scales. Regions with active agricultural production were identified using national agricultural census data (INEC, 2025), and recruitment efforts were concentrated in these areas to ensure that the sample reflected the geographic distribution of farming activities across the country. Farmers were initially contacted through field visits in major agricultural regions and through coordination with national agricultural institutions, including the Ministry of Agricultural Development (MIDA) and the Institute of Agricultural Innovation of Panama (IDIAP), which provided contact lists and facilitated introductions to local producers. These partnerships were important for reaching farmers across different production systems, from smallholders to commercial operations. To broaden representation, we complemented this process with snowball sampling, whereby interviewed farmers referred additional participants from their communities or networks.

The interviews consisted of two sections. The first collected demographic and socioeconomic information (e.g., age, gender, education level, household characteristics), and the second focused on agricultural practices and nitrogen management, including crop types grown, fertilizer sources used, and the amount of nitrogen applied per hectare. This structure provided both contextual information and detailed agronomic data necessary for modeling nitrogen application. All research procedures were reviewed and approved by the McGill University Research Ethics Board (REB #22-03-110) and the Smithsonian Tropical Research Institute Ethics Board (HS23014).

2.3.2. Drivers of nitrogen application

We evaluated 14 key drivers of nitrogen application. We selected these variables based on their relevance to nitrogen use, as identified in the literature or through their direct link to nitrogen application. We classified the factors into seven categories: environmental, demographic, agronomic, topographic, political, socioeconomic and conservation factors (see Table 1). This approach ensures a comprehensive understanding of the factors influencing nitrogen use across different contexts. The data sources for these variables are diverse, including Landsat images, census data, government reports and the interviews conducted in the present study (see Table 1). This range of sources allows for a robust and multidimensional analysis, capturing regional and temporal variations. Below, we briefly explain why we included each factor by category.

Environmental factors: We included precipitation and temperature as key variables because they can influence nitrogen fertilizer application (e.g. Guo and Chen, 2022; Zhang et al., 2024). This relationship may operate through straightforward mechanisms. For example, if a drought or excessive rainfall occurs, or is anticipated, at the time of fertilizer application, farmers may increase the fertilizer application to offset potential yield losses, or reduce it to avoid wasting inputs under suboptimal conditions (Billé and Rogna, 2022). To capture broader climatic patterns, we also include the variable "region", which incorporated the six hydroclimatic regions of Panama: Western Caribbean, Eastern Caribbean, Western Pacific, Central Pacific, Eastern Pacific, and Central Region. These regions are defined by CATHALAC (2016) based on an analysis of accumulated precipitation patterns across the country.

Table 1
Variables employed for the construction of the models and for prediction.

Variable Type	Variables Names	Resolution	Description	Sources
Dependent	Nitrogen Application	At district level	Average estimated nitrogen fertilizer use across agricultural districts (kg/ha)	Present Study
Environmental	Precipitation	1 km^2	Mean annual precipitation (mm/year) based on gridded climate data	CHELSA (Climatologies at high resolution for the earth's land surface areas)
Environmental	Temperature	1 km^2	Mean annual temperature (°C) derived from gridded climate datasets	CHELSA (Climatologies at high resolution for the earth's land surface areas)
Environmental	Climatic Regions	Six (6) regions	Classification of districts into six hydroclimatic regions (Western Caribbean, Eastern Caribbean, Western Pacific, Central Pacific, Eastern Pacific, and Central Region) based on CATHALAC (2016) to capture broader climatic patterns.	Centro del Agua del Trópico Húmedo para América Latina y el Caribe, CATHALAC. (2016). Una nueva regionalización climática de Panamá como aporte a la seguridad hídrica: Trabajo de la División de Investigación Aplicada y Desarrollo. 17 pp.
Topography	Digital Eleveation Models (DEM)	meters (m)	Average elevation of each district derived from digital elevation models (DEM)	USGS Earth Resources Observation And Science (EROS) Center. (2017). Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global [Data set]. U.S. Geological Survey. https://doi.org/10.5066/F7PR7TFT
Topography	Slope	meters (m)	Average terrain slope calculated from elevation data, indicating steepness of the landscape	USGS Earth Resources Observation And Science (EROS) Center. (2017). Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global [Data set]. U.S. Geological Survey. https://doi.org/10.5066/F7PR7TFT
Agronomic	Size of the Crops	At district level	Data were obtained from the surveys conducted as part of the present study. To predict values in other districts, we used the total agricultural area per crop at the district level (hectares).To predict values in other districts, we used the total agricultural area per crop at the district level (hectares).	Present Study and Agricultural Census of Panama (2011). https://www.inec.gob.pa/publicaciones/Default2.aspx?ID_CATEGORIA=15&ID_SUBCATEGORIA=60
Agronomic	Type of Crops	Crop Level	Data were obtained from the surveys conducted as part of the present study. For the prediction process in other districts, we identified the crops cultivated in each district.	Present Study and Agricultural Census of Panama (2011). https://www.inec.gob.pa/publicaciones/Default2.aspx?ID_CATEGORIA=15&ID_SUBCATEGORIA=60
Agronomic	Percentage of arable soils	At district level	Classification of soil based on agrological capacity into eight categories (Classes I–VIII) according to limitations such as depth, topography, fertility, erosion risk, and salinity. For analysis, these were grouped into two categories: arable land (Classes I–IV) and non-arable land (Classes V–VIII). Because both variables were perfectly correlated, only the "arable" category was included in the model.	Sistema Nacional de Información ambiental. Ministerio de Ambiente. https://geoportal.miambiente.gob.pa/portal/apps/webappviewer/index.html?id=68c87ca4c2d54a30b5064b0ac18bc76e
Agronomic	Total number of farms	At district level	Total number of registered farms in each district, based on agricultural census	Agricultural Census of Panama (2011). https://www.inec.gob.pa/publicaciones/Default2.aspx?ID_CATEGORIA=15&ID_SUBCATEGORIA=60
Political	Districts	NA	Administrative division representing the district-level unit used for analysis	Panama District Boundaries. Smithsonian Tropical Research Institute. https://stridata-si.opendata.arcgis.com/datasets/8f1c5499d3a8423888454cfee5b45586/explore
Political	Province	NA	Higher-level administrative division grouping districts within provinces	Panama Province Boundaries. Smithsonian Tropical Research Institute. https://stridata-si.opendata.arcgis.com/datasets/8f1c5499d3a8423888454cfee5b45586/explore
Demographics	Level of Education	NA	Categorical variable indicating the highest level of education attained by farmers (elementary school, high school, undergraduate, or graduate	Present Study
Demographics	Age	NA	Age of farmers, reported at the individual level from survey responses	Present Study
Socioeconomic	Percentage of Poverty	At district level	Proportion of the population living below the poverty line in each district, based on national statistics	Ministerio de Economía y Finanzas. (2020). Pobreza y desigualdad en Panamá: Mapas a nivel de distritos y corregimientos, 2015. https://www.mef.gob.pa/wp-content/uploads/2020/12/Pobreza-y-desigualdad-en-Panama-Mapas-a-nivel-de-Distritos-y-Corregimientos-2015.pdf
Socioeconomic	GINI index	At district level	Measure of income inequality within each district; higher values indicate greater inequality	Ministerio de Economía y Finanzas. (2020). Pobreza y desigualdad en Panamá: Mapas a nivel de distritos y corregimientos, 2015. https://www.mef.gob.pa/wp-content/uploads/2020/12/Pobreza-y-desigualdad-en-Panama-Mapas-a-nivel-de-Distritos-y-Corregimientos-2015.pdf
Conservation practices	Agriculture conservation Practice	At district level	District-level average of agricultural conservation practices implemented by farmers, based on yes/no responses to the 2011 National Agricultural Census. Farmers reported whether they: (1) protected wildlife, (2) used only organic products for pest and disease control, (3) carried out reforestation or silvopastoral activities, (4) documented or informed themselves on conservation and sustainable agriculture, (5) were interested in certification for good agricultural practices, (6) established live fences, (7) performed soil management and conservation practices, (8) protected water sources within farms, (9) controlled pesticide container disposal, and (10) avoided the use of burning.	Agricultural Census of Panama (2011). https://www.inec.gob.pa/publicaciones/Default2.aspx?ID_CATEGORIA=15&ID_SUBCATEGORIA=60

The inclusion of these regions into our analysis allows us to account for spatial heterogeneity in climate conditions, which may influence crop suitability and farmers' management practices, including fertilizer application strategies.

Demographic factors. We included demographic variables known to influence nitrogen fertilizer use, specifically age and education level. Data on age and education level were collected through surveys conducted as part of this study (Table S1). Previous research suggests that both age and education level significantly affect fertilizer application decisions; for instance, younger and more educated farmers are more likely to adopt efficient or reduced fertilizer use practices (Qiao et al., 2022).

Agronomic factors: In this category we included two variables collected during the present survey, type of crop and crop size, and one variable, total number of crops per district, which was obtained from the agricultural census. As expected, different crop types have distinct nutrient requirements, which directly influence both the amount and frequency of nitrogen applied by farmers. For instance, legumes such as beans, which can fix atmospheric nitrogen through symbiotic relationships with soil bacteria, typically require less synthetic nitrogen input (Giller, 2001). In contrast, crops like plantains have higher nitrogen demands and often receive more frequent applications to support their growth and fruit production (MIDA, 2012). Additionally, crop size may affect nitrogen application practices. For example, studies have shown that larger farms are more likely to adopt efficient fertilizer use strategies, resulting in higher fertilizer use efficiency (Ju et al., 2016).

Topographic factors. We selected two topographic variables, slope and elevation, derived from Digital Elevation Models (DEMs) (Table 1). These factors strongly influence the movement of water and nutrients through the soil, shaping surface runoff and erosion processes (Wang et al., 2023, 2024), and contributing to nitrogen losses from agricultural fields. Consequently, to minimize nutrient depletion, fertilizer application methods must be adapted to local conditions. For example, given the high erosion risk in hillslope areas, farmers often adjust their fertilizer use and management practices toward mid- and footslope zones, where soils retain more nutrients and are less susceptible to erosion (Amede et al., 2022).

Political factors. A key objective of this study is to predict nitrogen fertilizer application at a subnational scale in order to capture regional variability. To this end, we incorporated two levels of administrative boundaries in Panama into our model: provinces and districts. Panama is divided into 10 provinces and 82 districts, allowing for a nuanced analysis of spatial patterns in fertilizer use. These boundaries are critical, as political factors at both levels can influence agricultural practices through mechanisms such as fertilizer subsidies and technical training programs (He et al., 2022; Li et al., 2023). For example, district- or province-level institutions may implement training initiatives or incentive schemes that promote the adoption of more efficient fertilization methods. These regionally driven actions can have a direct impact on farmers' behavior, leading to variation in nitrogen application practices across administrative areas.

Socioeconomic factors: We used poverty and the coefficient of income inequality within a population (GINI index) to explore how economic factors shape nitrogen application in Panama. Both poverty and income inequality influence the amount and type of nitrogen applied, as financial constraints affect fertilizer use. It is anticipated that in areas with higher poverty levels, farmers may have limited access to quality fertilizers or efficient farming techniques, which could lead to lower nitrogen application. A higher GINI index, indicating greater income inequality, can also influence access to fertilizers and agricultural technologies. It is anticipated that in regions with high inequality, wealthier farmers may afford advanced methods, while poorer farmers have limited access, leading to uneven nitrogen application across the landscape.

Agricultural Conservation Practices: To capture the influence of conservation efforts on nitrogen application, we included a variable representing the adoption of agricultural conservation practices in Panama. This variable was derived from the National Agricultural Census, which featured a dedicated section on environmental practices in agriculture (INEC, 2025). In this section, all agricultural operations in the country reported whether they implemented each of ten standardized conservation and sustainable management practices (see Table 1). Using these responses, we calculated the average number of practices implemented per district. This district-level average serves as a proxy for the adoption of environmentally sustainable agricultural methods and was used as the variable *Agricultural Conservation Practices* in our analysis.

2.4. Statistical analysis

We assessed the impact of drivers listed in Table 1 on nitrogen application (dependent variable) using a series of linear mixed-effects models (LMMs). We included "District" as a random factor to account for the hierarchical data structure and variability across districts. The rationale for constructing the model at the district level was to align with the main objective of this present study which was to generate fine-scale estimates of nitrogen application in Panama. We believe this strategy is more appropriate for capturing spatial heterogeneity, as using national averages for nitrogen application would obscure important regional variation and limit the model's relevance for decision-making at the local scale. We assessed collinearity among covariates using Pearson's correlation matrix. When pairs of variables showed high collinearity ($r > 0.6$), we retained only one variable from each pair for the model. This was the case of the slope and Digital Elevation Model (elevation driver), which was shown 0.7 of correlation.

All analyses were conducted in R (version 4.4.1). Linear mixed-effects models (LMMs) were fitted using the *lmer(.)* function from the lme4 package (Bates et al., 2015). To better meet model assumptions of normality and homoscedasticity, all variables, including the response, were log-transformed using $log(x + 1)$. For interpretation and visualization of model predictions, the results were back-transformed using the inverse of the log transformation ($exp(x) - 1$). Model selection followed a backward stepwise procedure, where non-significant covariates (based on the highest p-values) were sequentially removed. The significance of predictors was assessed using Type III ANOVA, as implemented in the *anova(.)* function of the lmerTest package (Kuznetsova et al., 2017). To assess the relative fit of the models, reduced models were compared with the full model using the Akaike Information Criterion (AIC), with the final model being selected based on the lowest AIC value. To quantify the proportion of variance explained by the model, we calculated the marginal (fixed effects only) and conditional (fixed plus random effects) R^2 values using the *r.squaredGLMM* function from the MuMIn package.

To generate predictions of nitrogen application across districts, we used the final fitted model, (including only the significant predictors identified during model selection) and applied the *predict(.)* function with new district-level data as input.

3. Results

3.1. Descriptive analysis of the surveys

The survey encompassed 104 farmers managing a total of 148 farms, distributed across 34 of Panama's 82 districts and covering all 10 provinces (Table S2). Respondents had a mean age of 53.7 ± 12 years (range: 25–85). The majority of farmers were between 45 and 65 years old, with the highest numbers reported at ages 45–60. Younger farmers under 40 years old were relatively few, while farmers older than 75 years old were rare, represented by only a handful of individuals (Table S1). The educational background of the participants showed a predominance of individuals with a high school education. Specifically, 59 participants had completed high school, followed by 41 who had reached the undergraduate level. A smaller number reported completing only elementary school (3 participants), while just 1 participant had achieved a graduate degree (Table S1). Beyond these demographic features, the sample captured substantial diversity in farming contexts, reflecting both smallholder and commercial production systems across the country. Geographically, surveyed farmers were primarily located in agriculturally intensive provinces such as Chiriquí (31 respondents), Veraguas (25), and Panamá (23). Other provinces with moderate representation included Herrera, Coclé, Los Santos, Darién, and Panamá Oeste, while fewer participants were interviewed in Colón (4) and Bocas del Toro (3) (Table S2), reflecting regional differences in farming activity consistent with national trends. This distribution provides a broad representation of Panama's major agricultural regions and ensures that the survey captures variation in climate and production systems that shape fertilizer practices across the country.

The survey captured key characteristics of agricultural practices among farmers across Panama. Respondents reported cultivating a total of 12 distinct crop types (Table S3), encompassing both staple and export-oriented crops. Rice was the most widely reported crop, grown by 61 farms and representing 8.24 % of the national rice area surveyed. Coffee was produced by 27 farms, accounting for 0.77 % of its national crop area, while maize (corn) was reported by 21 farms with a survey coverage of 1.88 %, reflecting national trends where these staples dominate agricultural production (INEC, 2025). Other important crops included plantain (11 farms; 1.17 % coverage), banana (3 farms; 5.29 %), and oil palm (5 farms; 18.39 %). Orange production was represented by 9 farms (21.54 % coverage), while sugar cane (4 farms; 5.33 %) and pineapple (2 farms; 2.81 %) also showed notable surveyed proportions. Less common crops such as pigeon pea (2 farms; 0.76 %), common bean (1 farm; 0.03 %), and watermelon (2 farms; 0.29 %), were reported by only a few farms.

Nitrogen application rates also varied by crop type (Fig. 1). Bananas and pineapples received the highest inputs, with mean rates of 278 ± 0 kg ha^{-1} yr^{-1} and 189 ± 8 kg ha^{-1} yr^{-1}, respectively (Fig. 1). In contrast, pigeon pea (34 ± 26 kg ha^{-1} yr^{-1}), oranges (32 ± 70 kg ha^{-1} yr^{-1}), and coffee (40 ± 60 kg ha^{-1} yr^{-1}) received substantially lower nitrogen inputs, reflecting both agronomic requirements and farmer management decisions. Rice and corn, two of the most widely grown staple crops in the country, had intermediate application rates, averaging 124 ± 64 kg ha^{-1} yr^{-1} and 149 ± 46 kg ha^{-1} yr^{-1}, respectively (Fig. 1). These patterns highlight the diversity in fertilization practices across crops in Panama.

3.2. Drivers of nitrogen application

The final model, which included only significant fixed effects and accounted for district-level variation as a random effect, explained 64.4 % of the variance in log-transformed nitrogen application rates (marginal $R^2 = 0.64$; conditional $R^2 = 0.64$). This indicates that most of the variability in nitrogen application was captured by the fixed effects, with minimal additional variance attributed to differences among districts after accounting for these predictors.

We found that nitrogen application rates varied significantly according to agronomic, political, and conservation-related factors (Fig. 2). Among the agronomic factors, crop type significantly influenced nitrogen use ($F_{11,125} = 2.60$, $p = 0.005$), indicating variation in application levels among different crops. The total number of farms in the district showed a negative relationship with nitrogen application ($F_{1,125} = 5.42$, $p = 0.022$; $\beta = -0.47$), suggesting that an increase in the number of farms within a district was associated with lower nitrogen use. Farm size had a positive association with nitrogen application ($F_{1,125} = 24.45$, $p < 0.001$; $\beta = 0.35$), indicating that larger farms tended to apply more nitrogen per area.

Among the political factors, province had a significant effect on nitrogen application ($F_{8,125} = 4.39$, $p < 0.001$), indicating spatial differences in fertilizer use across regions.

For conservation-related factors, the mean proportion of farms implementing conservation practices in each district (log-transformed) showed a significant negative relationship with nitrogen application ($F_{1,125} = 4.60$, $p = 0.034$; $\beta = -5.93$), suggesting that districts with greater adoption of conservation practices tended to use less nitrogen.

3.3. Spatial prediction across districts in Panama

We used the final model, selected based on the lowest AIC and including only significant fixed effects, to predict nitrogen application rates across all districts in Panama. Predictor data were obtained from the Agricultural Census of Panama (INEC, 2025) and correspond only to

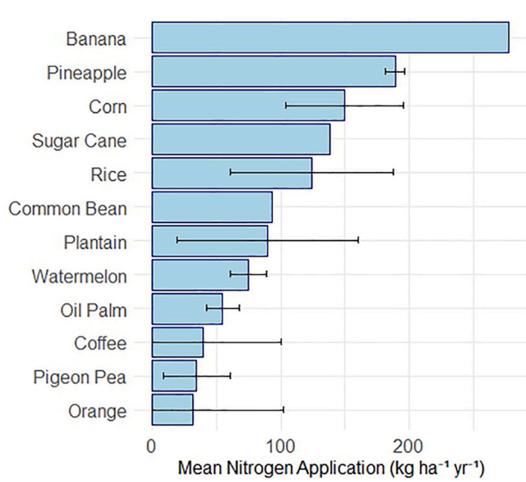

Fig. 1. Mean nitrogen application rates (kg ha^{-1} yr^{-1}) across different crop types in Panama. Bars represent mean values, and error bars indicate standard errors. Banana and pineapple received the highest nitrogen inputs, while perennial and leguminous crops such as orange and pigeon pea had the lowest. For banana, nitrogen data were reported by a single producer managing three farms, and for common bean by one producer with a single farm; therefore, no variance (error bars) could be calculated. See Supplementary Table S3 for details on the number of farms interviewed per crop.

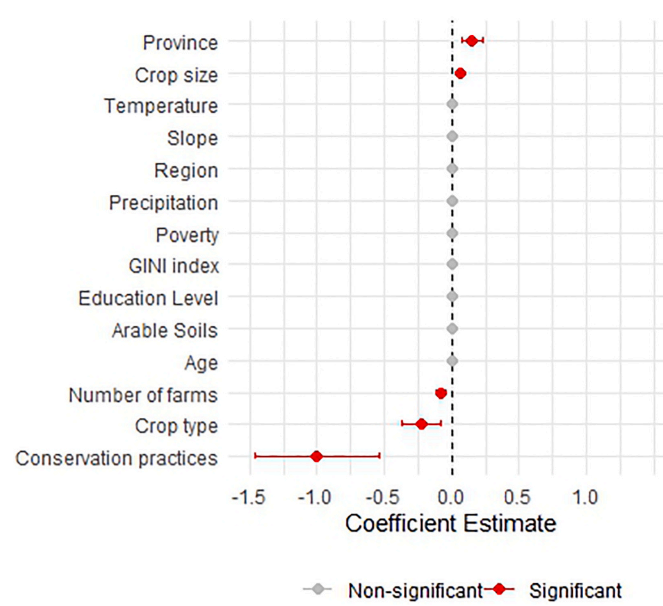

Fig. 2. Standardized coefficient estimates from the linear model predicting nitrogen application across districts in Panama. Red points indicate statistically significant predictors ($p < 0.05$), while gray points represent non-significant variables.

the variables included in the final model (i.e., Province, Crop type, Conservation practices, Number of farms and Crop size). Predicted nitrogen application rates were highest in several districts within the central and western regions of Panama (Fig. 3). For example, Aguadulce in the province of Coclé showed the highest predicted rate (1032.6 kg ha^{-1} yr^{-1}; 8.52 million kg yr^{-1}), followed by Remedios in the province of Chiriquí (885.0 kg ha^{-1} yr^{-1}; 0.91 million kg yr^{-1}), Las Tablas in the province of Los Santos (884.3 kg ha^{-1} yr^{-1}; 7.32 million kg yr^{-1}), Pedasí in Los Santos (866.3 kg ha^{-1} yr^{-1}; 1.56 million kg yr^{-1}), and Alanje in Chiriquí (842.0 kg ha^{-1} yr^{-1}; 13.62 million kg yr^{-1}) (Table S4). These predicted hotspots of nitrogen use correspond to areas with more intensive agricultural activity, aligning with known patterns of crop production in these regions. In contrast, many districts in the eastern and northern provinces showed much lower predicted nitrogen application rates, reflecting the predominance of less intensive agricultural activity in these areas. For example, several districts in the province of Colón such as Colón (11.94 kg ha^{-1} yr^{-1}; 837.41 kg yr^{-1}), Chagres (10.92 kg ha^{-1} yr^{-1}; 650.17 kg yr^{-1}), and Donoso (10.34 kg ha^{-1} yr^{-1}; 296.59 kg yr^{-1}) (Table S4), had some of the lowest predicted nitrogen application rates in the country. Similarly low values were observed in parts of the province of Veraguas, including Santa Fe (38.98 kg ha^{-1} yr^{-1}; 15, 636.10 kg yr^{-1}) and Calobre (51.41 kg ha^{-1} yr^{-1}; 110,115.16 kg yr^{-1}), as well as in Bocas del Toro, where Chiriquí Grande (39.93 kg ha^{-1} yr^{-1}; 6762.87 kg yr^{-1}) and the Bocas del Toro district (61.53 kg ha^{-1} yr^{-1}; 1349.37 kg yr^{-1}) (Table S4), exhibited comparatively modest nitrogen inputs.

4. Discussion

Efficient nitrogen management is essential for advancing sustainable agriculture and mitigating environmental pollution. Yet, the drivers of nitrogen fertilizer application in tropical regions remain poorly understood, particularly at subnational scales. In this study, we applied statistical models to identify the main factors influencing nitrogen application in Panama and to predict its spatial distribution across the country's districts. Our findings demonstrate that agronomic, political, and conservation factors are key determinants of nitrogen application in Panama, clearly indicating the necessity of incorporating these drivers into efforts to promote sustainable nitrogen management. We also found substantial spatial variability across districts in terms of nitrogen application, with higher application rates concentrated in the central and western regions of Panama. These results highlight the need to move beyond one-size-fits-all approaches and adopt regionally tailored nitrogen management strategies in response to the observed spatial heterogeneity in nitrogen application across districts. Overall, our results highlight the complexity of fertilizer application in Panama and provide opportunities to improve policy design and inform context-specific interventions that advance both agricultural productivity and environmental sustainability.

4.1. *Agronomic drivers of nitrogen application in Panama*

Agronomic factors play a central role in shaping fertilizer application patterns, as they directly influence nutrient demands and farming practices. Factors such as the type of crop grown, the size of farms, and the overall agricultural production systems can significantly affect how much nitrogen is applied. In the present study we found that nitrogen application rates in Panama varied significantly based on agronomic factors, specifically crop type, farm size, and the total number of farms per district (Fig. 2). Among these factors, crop type was perhaps the most intuitive, as it is expected that different crops have distinct nutrient requirements and, consequently, different fertilizer needs. For example, crops such as banana and pineapple typically require higher amount of nitrogen fertilizer to support their growth, whereas legumes such as pigeon peas require less nitrogen input due to their ability to fix atmospheric nitrogen (Mondal et al., 2023), a pattern that aligns with our findings.

Additionally, we observed that several of Panama's key export fruits received relatively high levels of nitrogen application. In particular, banana and pineapple, two of the country's major export fruit products (INEC, 2025), had among the highest nitrogen application rates per hectare in our study (Fig. 1). The elevated nitrogen use in these export-oriented crops likely reflects farmers' efforts to maximize yields and maintain consistency with international market standards. These findings suggest that fertilizer decisions are shaped not only by the nutrient requirements of crops but also by their economic value, highlighting the role of market incentives alongside agronomic needs. This aligns with previous research showing that economic incentives, in our case the potential for higher returns from export-oriented crops, influence fertilizer application decisions (Yadav et al., 1997;

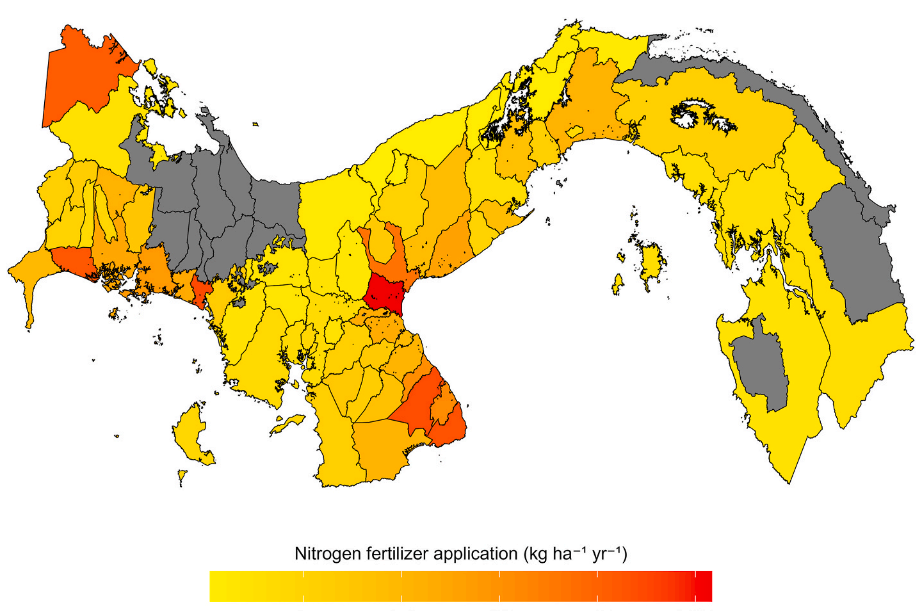

Fig. 3. Predicted nitrogen fertilizer application (kg ha^{-1} yr^{-1}) across Panama. Districts with the highest application rates are shown in red and dark orange. Gray areas indicate regions where no data were available.

Martínez-Dalmau et al., 2021; Begho et al., 2022).

We also found that farm size significantly influences nitrogen application rates in Panama ($\beta = 0.352$, $p < 0.001$), with larger farms applying more nitrogen per hectare. Based on our model, a 1 % increase in crop size is associated with a 0.35 % increase in nitrogen application per hectare. The relationship between farm size and fertilizer use, however, varies across agricultural settings. In some contexts, consistent with our findings, larger farms apply more nitrogen per unit area due to better access to inputs, markets, and agricultural credit (Aryal et al., 2021; Waithaka et al., 2007). Conversely, other studies have reported a negative correlation, where larger farms apply less fertilizer per hectare while maintaining or improving yields, often through more efficient management and the adoption of advanced technologies (Ju et al., 2016; Wu et al., 2018). In China, agricultural support and fertilizer policies have lowered the effective cost of synthetic fertilizers, reducing economic constraints on fertilizer use and contributing to high application rates and overuse (Wu et al., 2019; Zhang et al., 2015). In Panama, however, many small-scale farmers face financial constraints, limited access to agricultural inputs, and reduced technical support (MAPA, 2021), all of which restrict their ability to purchase and apply nitrogen fertilizers. These challenges have been further amplified during periods of fertilizer price volatility, such as the COVID-19 pandemic, when sharp price increases led some farmers to reduce fertilizer use even further. Larger commercial operations, by contrast, typically have greater purchasing power and more stable access to input markets, enabling them to apply higher nitrogen rates. These contrasting examples highlight that the relationship between farm size and nitrogen application is context dependent and shaped by both economic conditions and management capacities across agricultural systems.

Another important agronomic factor influencing nitrogen application was the number of farms at the district level. We found a significant negative relationship between the number of farms per district and nitrogen application rates ($\beta = -0.467$, $p = 0.021$), indicating that districts with more farms tend to apply less nitrogen per hectare. Specifically, our model suggests that a 1 % increase in the number of farms is associated with a 0.47 % reduction in nitrogen use per hectare. This observation may result from the predominance of smallholder or subsistence farming systems in districts. These types of systems often face limited access to financial resources, extension services, and modern technologies (Touch et al., 2024), which in turn constrains the use of nitrogen fertilizers. Evidence for this interpretation comes from national official statistics indicating that approximately 67 % of agricultural holdings in Panama are smaller than 3 ha and operate within a subsistence economy, often lacking adequate infrastructure, financial services, technical assistance, and access to modern inputs (INEC, 2025; MAPA, 2021). In addition to these structural limitations, some small-scale farmers in Panama have intentionally adopted agroecological strategies (Santamaría-Guerra and González, 2017). These approaches, which rely on traditional ecological knowledge and diversified cropping systems, allow farmers to maintain productivity with minimal reliance on external inputs, including synthetic fertilizers. Taken together, the high prevalence of smallholder farmers and the adoption of agroecological farming systems in Panama may further explain the lower nitrogen application observed in districts with a higher number of farms.

4.2. Conservation practices reduce nitrogen application at district scale

Agricultural conservation practices are essential for promoting sustainable farming by enhancing soil health, reducing input dependency, and mitigating environmental impacts (Li et al., 2018; Wagena and Easton, 2018; Prokopy et al., 2019; Teng et al., 2024). These practices encompass techniques such as cover cropping, reduced tillage, and organic amendments (Crystal-Ornelas et al., 2021; Teng et al., 2024; García et al., 2016), all aimed at enhancing long-term productivity while optimizing the use of synthetic fertilizers. Our analysis found that agricultural conservation practices implemented by farmers were a significant predictor of nitrogen application rates at the district level ($\beta = -5.93$, $p = 0.034$), with higher adoption of conservation practices associated with lower nitrogen application. In our study, this variable was derived from the National Agricultural Census of Panama, which recorded whether farmers engaged in a range of agricultural conservation practices, such as protecting wildlife, managing soils, using organic pest control, protecting water sources, and establishing live fences or silvopastoral systems (Table 1). Conservation practices are widely recognized as effective strategies for reducing nitrogen fertilizer application or loss in agricultural systems (Devkota et al., 2015). For example, Duan et al. (2016) demonstrated that integrating organic fertilizers, such as manure, with chemical fertilizers significantly reduced total nitrogen losses in rain-fed cropping systems, while also enhancing soil nitrogen storage and improving nitrogen use efficiency. Similarly, Kader et al. (2022) found that long-term conservation agriculture, including strip tillage and residue retention, increased nitrogen use efficiency, land equivalent ratio, and soil carbon stocks in a subtropical rice-based system. Collectively, these examples illustrate the potential of conservation-oriented agriculture to enhance sustainability, reduce nitrogen pollution, and improve fertilizer efficiency, reinforcing the relevance of our findings.

Importantly, because the relationship between agricultural conservation and nitrogen application was modeled using log-transformed variables, reductions in nitrogen use are slightly more pronounced at lower levels of conservation adoption. In other words, initial increases in the percentage of farmers adopting conservation practices, from very low to moderate levels, tend to yield considerable effects on nitrogen application reduction at district scale. For instance, increasing conservation adoption from 15 % to 25 % at district level leads to a 39 % reduction in nitrogen application, compared to a 32.7 % reduction when adoption rises from 45 % to 55 %. While this difference is not large, it suggests that districts with lower conservation engagement may see slightly greater benefits from initial efforts to promote adoption. Nonetheless, reductions in nitrogen application remain meaningful across all adoption levels, underscoring the value of agricultural conservation practices as a consistent strategy for improving both environmental outcomes and fertilizer management.

4.3. Spatial variation in nitrogen application across Panama

Nitrogen application data are usually reported at the national level, masking local differences and limiting the design of targeted management strategies. In this study, we used a linear mixed-effects model to predict nitrogen application rates at the district level, producing the first nitrogen application map for Panama (Fig. 3). The model shows that districts in central and southwestern Panama have the highest predicted nitrogen use, aligning with areas of intensive crop production. For example, Alanje and David in the western Pacific, along with Aguadulce and Natá in central Panama, are major producers of rice and sugarcane (INEC, 2025), likely driving the high nitrogen inputs in these areas. In contrast, the central Caribbean region shows much lower nitrogen application, consistent with its sparse agricultural activity and low farm density (INEC, 2025). Additionally, our data show that districts on the Pacific side of the country have medium to high nitrogen application rates compared to those on the Caribbean side. This pattern aligns with the distribution of agricultural land, which is largely concentrated along the Pacific, reinforcing the spatial trends observed in this study. This district-level analysis offers a clearer view of fertilizer distribution and can inform more effective, region-specific agricultural and environmental policies.

4.4. Implications for sustainable agricultural management

Our findings have important implications for agricultural management efforts in Panama. Our analysis emphasizes that crop type, farm size, and the prevalence of smallholder farming are important to understanding nitrogen use across the country. For example, districts dominated by export-oriented, high-input crops such as banana and pineapple exhibit higher nitrogen application rates, reflecting both the biological needs of these crops and economic incentives to maximize yields. Meanwhile, districts with smaller farms and greater land fragmentation tend to apply significantly less nitrogen, likely due to constraints in access to agricultural inputs, technical assistance, and capital. These contrasting patterns underscore the need for differentiated policy strategies that address the distinct realities of commercial and subsistence farmers. While larger commercial farms may benefit from policies promoting nitrogen-use efficiency and advanced technologies, smallholders require improved access to resources, infrastructure, and technical support that enable them to adopt sustainable practices while enhancing productivity.

Another key implication of our findings is that agricultural conservation practices can help reduce nitrogen use while supporting broader sustainability goals. Taking this into consideration, wider adoption of conservation practices should be encouraged across the country. We believe this can be effectively promoted through two complementary strategies. First, apply financial incentives to support the adoption of conservation-based farming practices. This can involve introducing new forms of support such as direct payments, subsidies, or tax reductions for farmers who implement agricultural practices that can reduce nitrogen loss, including cover cropping, soil conservation, and nutrient management planning. Second, strengthen and expand agricultural extension services to provide farmers with the technical knowledge and tools needed to adopt conservation practices effectively. Extension support can help farmers overcome key barriers to improved nitrogen management, such as limited technical knowledge, high initial investment costs, uncertainty about economic returns, and perceived risks associated with adopting unfamiliar practices, making conservation a more viable and attractive option. Together, these strategies offer a practical and effective approach for promoting sustainable nitrogen use while supporting farmer livelihoods and long-term agricultural resilience.

Another important implication of our findings is the utility of the district-level nitrogen application map as a decision-support tool for agricultural and environmental management across Panama. By revealing spatial heterogeneity in nitrogen fertilizer application, the map enables more targeted nitrogen reduction strategies, particularly in districts identified as hotspots of intensive application. These areas may benefit from tailored interventions such as nutrient management planning, farmer education programs, or policy enforcement. Additionally, in a context of limited institutional capacity and resources, this map can serve as a tool for prioritizing where extension services or monitoring efforts should be concentrated to maximize environmental and agronomic returns. Importantly, many of the districts identified as hotspots of nitrogen application (e.g., Alanje and Remedios in the province of Chiriquí, Las Tablas and Pedasí in the province of Los Santos or Aguadulce and Natá in the province of Coclé) are also located in watersheds that drain directly into coastal and estuarine environments. As such, these areas represent not only agricultural management priorities but also critical intervention zones to prevent nutrient runoff and protect coastal ecosystems from nitrogen-driven eutrophication. This underscores the importance of considering both terrestrial and marine impacts of fertilizer use, suggesting that future research and policy should adopt integrated watershed–coastal approaches to nitrogen management in Panama.

The district-level insights generated by this study not only advance understanding of nitrogen application but also align closely with broader national and international goals related to sustainable agriculture and climate resilience. At the national level, Panama's National Climate Action Plan (PNAC) identifies sustainable agriculture as a strategic pillar for reducing greenhouse gas emissions, including through the optimization of nitrogen fertilizer use in crops such as rice via best management practices (MiAmbiente, 2022). Our district-level nitrogen map provides a critical tool to support such efforts by identifying regions where fertilizer use is most intensive and where interventions could be prioritized. Additionally, Panama has faced increasing economic and production vulnerability due to disruptions in the international fertilizer market, with import prices rising by 155 % in early 2022 despite a 29.5 % decline in volume (IICA, 2022). This underscores the urgency of improving fertilizer efficiency and building resilience in national food systems. By identifying where nitrogen application is highest and which agronomic and conservation factors drive these patterns, our study provides evidence-based guidance to optimize fertilizer allocation, promote best practices, and reduce dependence on costly imports. These insights contribute directly to national efforts to improve nitrogen use efficiency and strengthen climate resilience in agriculture.

Our findings that smallholders employing traditional practices tend to apply less synthetic nitrogen raise important questions for future research and management. Lower nitrogen application rates in these systems may result either from limited access to agricultural inputs or from intentional management choices aligned with traditional smallholder farming systems focused on meeting household or local food requirements. However, the extent to which moderate increases in nitrogen inputs can enhance yields while maintaining environmental sustainability remains unclear. Future studies should assess yield responses under smallholder conditions to identify whether moderate increases in nitrogen application can enhance productivity without increasing environmental risks. In contrast, larger commercial farms, which apply more nitrogen per hectare, are often driven by market incentives to maximize returns and expand cultivated areas to maintain competitive production costs. This dynamic may drive agricultural expansion into ecologically sensitive areas, especially in frontier zones near wetlands or coastal regions that have historically been affected by agricultural conversion and related disturbances in Panama (López-Angarita et al., 2021). Consequently, the expansion of commercial operations could undermine nitrogen reductions achieved through conservation practices or policy interventions. Future research should focus on designing integrated nitrogen management and land-use planning frameworks that promote sustainable intensification, enhancing yields on existing farmland while preventing further encroachment into ecologically sensitive areas.

Although our analysis is specific to Panama, several aspects of our findings may have broader relevance for other tropical agricultural regions that share similar structural characteristics. Many Latin American countries, for instance, exhibit a dual agricultural landscape in which high-input farming coexists with traditional smallholder systems, often under uneven access to fertilizers, technical assistance, and market opportunities (Austin et al., 2013; Cunha-Zeri and Ometto, 2021; Martinelli et al., 2006; Ometto et al., 2020). These shared features suggest that some of the socioeconomic and agronomic drivers identified here, such as the influence of crop type, farm size, and conservation practice adoption, could operate in comparable ways elsewhere, although the degree of overlap will depend on factors such as local governance structures, management systems, historical land-use patterns, and underlying biophysical conditions. In addition, Panama's reliance on fertilizer imports and its spatial environmental and socioeconomic heterogeneity resemble conditions found across parts of Latin America. For these reasons, the district-level analytical framework applied in this study, which integrates national statistics with survey-based agronomic information, should be viewed as a potentially transferable approach for examining nitrogen-application variability in data-limited tropical landscapes, while recognizing that its applicability must be evaluated in relation to each region's specific institutional and agronomic context.

4.5. *Limitations*

Our study has several limitations that should be considered for future work. First, the spatial coverage of the data is limited due to the number and distribution of interview sites. As a result, the analysis may not fully represent the range of agricultural practices across all regions, particularly those used by groups such as indigenous communities and small-scale vegetable producers. For example, indigenous farmers often use traditional agroecological methods that rely on minimal or no external inputs (Santamaría-Guerra and González, 2017), which are not part of our study. Similarly, districts with intensive horticultural production, such as Tierras Altas in the province of Chiriquí, which includes areas like Cerro Punta known for vegetable cultivation (Shah, 2006), may follow fertilization practices that differ from those reflected in the aggregated crop categories used in this study.

Second, our analysis relied on a simplified representation of complex agricultural systems and excluded several variables that may significantly influence nitrogen application. In particular, we did not account for factors such as soil management history, government subsidies, and farmer socio dynamics, all of which can shape fertilizer use. Subsidies, for instance, have been shown to reduce fertilizer use when tied to efficiency-enhancing investments. In China, recent agriculture subsidies led to a 7.2 % reduction in fertilizer use, particularly through mechanization and farm expansion (Fan et al., 2023). Similarly, a 100 % increase in subsidies was associated with a 3.4 % decline in fertilizer expenditure per hectare (Guo et al., 2021). Likewise, social factors, such as participation in cooperatives, access to technical training, or involvement in knowledge-sharing networks, can influence both fertilizer management decisions and the adoption of conservation practices like the use of organic fertilizers and agricultural technologies (Wang et al., 2018; Zheng et al., 2022; Qiao et al., 2022).

4.6. Conclusion

Nitrogen fertilizers play a critical role in food production, but their overuse and mismanagement can lead to significant environmental degradation and reduced input efficiency. Effective nitrogen management requires a clear understanding of the factors that influence fertilizer application. This study provides new insight into the patterns and drivers of nitrogen application in Panama, highlighting the influence of crop type, farm size, and adoption of conservation practices. By developing the first district-level nitrogen application map for the country, we offer a practical tool to support conservation planning and guide region-specific interventions. This spatial framework enables the identification of high-use areas where targeted strategies, such as the promotion of conservation practices, can reduce environmental impacts. Our findings can inform agricultural policy and program design, contributing to more efficient and sustainable nitrogen management at both national and subnational levels.

CRediT authorship contribution statement

Jorge Manuel Morales-Saldaña: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hector M. Guzman:** Writing – review & editing, Supervision, Resources, Investigation. **Brian Leung:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Brian Legun reports financial support was provided by Quebec Research Fund Society and Culture. Brian Leung reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Brian Leung reports financial support was provided by McGill Sustainability Systems Initiative. Hector M. Guzman reports financial support was provided by Sistema Nacional de Investigación (SNI), Panama. Jorge Manuel Morales Saldana reports financial support was provided by Secretaría Nacional de Ciencia, Tecnología e Innovación. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.128371.

Data availability

Data will be made available on request.

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