INTERSECTING PATHWAYS: BIODIVERSITY LOSS, GREENHOUSE GAS EMISSIONS, AND SOCIOECONOMIC VULNERABILITIES IN PERU'S HIGH CARBON STOCK REGIONS

DIC
2024

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DOI: 10.4160/cip.2024.12.001

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Citation:
Pradel, W.; Juárez, H.; Gutiérrez, D.; Casallas, I.; Sosa, C. 2024. Intersecting Pathways: Biodiversity Loss, Greenhouse Gas Emissions, and Socioeconomic Vulnerabilities in Peru's High Carbon Stock Regions. Lima, Peru: International Potato Center. 27 p. DOI: 10.4160/cip.2024.12.001.

Design and Layout:
Communications Department

December 2024

CIP also thanks all donors and organizations that globally support its work through their contributions to the CGIAR Trust Fund: www.cgiar.org/funders

Content

1 Abstract

Peru's high carbon stock regions, encompassing some of the world's most biodiverse ecosystems, face mounting pressures from deforestation, land use change, and socioeconomic vulnerabilities. This study explores the spatial overlap between biodiversity loss, greenhouse gas (GHG) emissions, and socioeconomic challenges—including poverty, human development, and childhood stunting—across 252 districts in Peru's Amazon and Andean regions. Employing Local Indicators of Spatial Association (LISA) and socioeconomic data from 2016–2019, the analysis reveals weak-to-moderate correlations between environmental degradation and socioeconomic factors.

Despite limited global associations, the study identifies critical hotspots, particularly in San Martín, Ucayali, and Huánuco, where poverty, deforestation, and low human development index (HDI) intersect. These findings highlight the urgent need for integrated strategies to mitigate deforestation, promote socioeconomic development, and achieve Sustainable Development Goals (SDGs). By prioritizing interventions in these areas, Peru can advance its commitments to climate change mitigation and biodiversity conservation while addressing persistent social inequities.

2 Introduction

The complexity of global sustainability challenges demands a comprehensive and interdisciplinary approach. The sustainable development agenda is the recognition that the environment, economy, and society are deeply interconnected, requiring integrated solutions that address multiple Sustainable Development Goals (SDGs) simultaneously (Luttikhuis et al., 2023). In this context, understanding the interconnections between biodiversity, land use change, greenhouse gas (GHG) emissions, and socioeconomic indicators such as poverty, gross domestic product (GDP), and stunting at different scales, is crucial to formulating effective conservation strategies.

Peru is home of some of the world's most biodiverse ecosystems, which play a crucial role in facilitating the exchange of energy, water, and various chemical compounds within the system and with the environment. These exchanges are driven by physical and ecological processes operating on daily and seasonal timescales. Key factors influencing these dynamics include vegetation and soil properties, such as albedo, which controls the balance of solar energy absorbed and reflected by the Earth's surface, and soil water availability, which regulates the hydrological cycle, latent heat fluxes, and greenhouse gas emissions (Nunes et al., 2020).

Peru is one of the world’s most biodiverse countries, housing approximately 84 of the 117 life zones known on Earth, as well as ecosystems ranging from the Amazon rainforest to Andean highlands. With over 25,000 plant species, 1,800 bird species, and thousands of unique amphibian, reptile, and mammal species (MINAM, 2019). The Amazon Basin in Peru is especially significant, accounting for a substantial portion of the country’s carbon storage and contributing to global climate regulation.

However, despite the country’s enormous biodiversity and related ecosystem services, Peru’s ecosystems are under immense pressure from human activity. The most severe threat comes from deforestation, largely driven by agricultural expansion, illegal timber extraction, infrastructure projects, mining, but also severe drought (Lapola et al., 2023; Mostiga et al., 2024). In particular, the conversion of forested lands into agricultural plots for crops like coffee, cacao, and palm oil (Vijay et al, 2018; Gutiérrez-Vélez and DeFries, 2013), has accelerated the loss of biodiversity. These trends have implications not only for conservation but also for GHG emissions, as forests play a vital role in sequestering carbon. Forest loss leads to the release of stored carbon, contributing to climate change (Asner et al. 2010).

The aim of this research is to identify key areas in Peru where biodiversity loss, GHG emissions, and socioeconomic challenges overlap, creating environmental “hotspots” that require urgent attention. By mapping these areas, we can better understand the spatial distribution of environmental pressures and prioritize interventions that address multiple SDGs simultaneously. For example, areas of high deforestation and carbon emissions may also be regions where poverty rates and stunting are highest, indicating the need for integrated strategies that promote both conservation and socioeconomic development.

This study presents a comprehensive spatial analysis exploring the interconnections between socioeconomic variables and land use change across districts the eastern slope of the Andes and the Amazon in Peru, between two time periods: 2017-2019 and 2016-2018 analyzing socio economic data in conjunction with land use change and deforestation data.

3 Background

3.1 Deforestation and Land Use Change in Peru

Over the last several decades, deforestation has emerged as a critical environmental issue in Peru. From the early 2000s to the present, the rate of deforestation in the Peruvian Amazon has been alarming, with significant portions of primary forest cleared for agriculture, illegal gold mining, and other forms of land use. According to Mostiga et al. (2024) the rate of forest loss grew from 115,000 ha/year in 1990–2000 to 125,000 ha/year in 2000–2010, and to 172,000 ha/year in the last decade, despite the efforts from the government to increase the protected areas surface. Most of forest loss events in the Peruvian Amazon are small-scale with less <5 hectares, and it occurs mainly in the hotspots in Huánuco, Ucayali, San Martin and Madre de Dios (Finer and Novoa, 2017).

One of the driving forces behind land use change in Peru is the demand for agricultural land. Shifting cultivation, a common practice in the Amazon, often involves clearing forests to make way for crop production. While this may provide short-term economic benefits for local communities, it affects long-term environmental sustainability by degrading soil quality and contributing to biodiversity loss as well as reduce energy and water balance (Davidson et al., 2012). Additionally, illegal logging and mining activities further exacerbate land use change, often occurring in remote areas where enforcement of environmental regulations is weak.

Land use change in Peru is not uniform across the country. While the Amazon experiences the highest rates of deforestation, other regions such as the Andean highlands and coastal zones are also affected by land degradation, albeit for different reasons. In the highlands, overgrazing and unsustainable agricultural practices have led to soil erosion and the loss of native vegetation. Along the coast, urban expansion and infrastructure development are putting pressure on ecosystems that are critical for biodiversity and carbon sequestration.

3.2 Greenhouse Gas Emissions in Areas of High Carbon Stocks in Peru

The relationship between land use change and GHG emissions in Peru is particularly pronounced in areas of high carbon stocks, such as the Amazon rainforest. Forests act as carbon sinks, absorbing CO_2 from the atmosphere and storing it in biomass and soils. When forests are cleared or degraded, this stored carbon is released back into the atmosphere, contributing to global GHG emissions. As deforestation rates in Peru continue to rise, so too do emissions, making land use change a key driver of the country's carbon footprint (MINAM, 2016).

Peru's GHG emissions are primarily derived from the land use, land-use change, and forestry sector. According to the national inventory, this sector accounted for nearly half of the country's total emissions in recent years, with deforestation being the primary problem. Other sources of emissions include energy production, transportation, and industrial processes, but none have the same scale of impact as deforestation (Naughton-Treves, 2004). The high carbon density of Peruvian forests means that even small-scale land conversion can lead to significant emissions.

The trends in GHG emissions in Peru are concerning from both a national and global perspective. As one of the world's most carbon-rich countries, the loss of Peruvian forests represents a significant source of emissions that undermines efforts to mitigate climate change. Moreover, the areas most affected by deforestation—such as the Amazon—are also critical for maintaining biodiversity and supporting indigenous livelihoods, creating a complex nexus of environmental and social issues.

3.3 Socioeconomic Dimensions: Poverty, GDP, and Stunting in Peru

The environmental challenges faced by Peru are closely linked to its socioeconomic context. Poverty remains a significant issue in many regions, particularly in rural and indigenous communities that are heavily dependent on natural resources for their livelihoods (Zwane, 2007). In areas such as the Amazon, where deforestation is most prevalent, poverty rates are disproportionately high. These communities often rely on agriculture, hunting, and small-scale forestry, all of which are vulnerable to environmental degradation (Mostiga et al, 2024).

In addition to poverty, GDP growth in Peru has been uneven, with much of the economic development concentrated in urban centers. While the country has experienced economic growth over the past few decades, this has not necessarily translated into improved living conditions for rural populations. The gap between urban and rural areas is particularly pronounced when it comes to access to basic services, education, and healthcare (Menton and Cronkleton, 2019).

Stunting, a condition caused by chronic malnutrition, is another major issue affecting rural populations in Peru (Rougeaux et al., 2022). High rates of stunting are also located in areas with high levels of deforestation and environmental degradation. This suggests a link between environmental health and human health, as deforestation and land use change can disrupt food systems, reduce agricultural productivity, and limit access to nutritious food. Despite, anecdotal evidence, there is no evidence with data that there is a pattern on the overlap between health, poverty and deforestation, which this study intends to elucidate.

Amazon forest degradation can reduce dry-season evapotranspiration by up to 34% and cause as much biodiversity loss as deforestation in human-modified landscapes, generating uneven socioeconomic burdens, mainly to forest dwellers (Lapola et al., 2023)

4 Methodology

The study focused on 252 districts within the Sierra and Selva regions of Peru, areas selected based on the availability of comprehensive data related to land use and deforestation. Data on deforested areas were compiled by the staff at the International Center for Potato (CIP), while other variables were obtained from the National Statistical and Informatic Institute (INEI for its Spanish acronyms). The dataset included 29 variables grouped into three categories: socioeconomic, biophysical, and land use. These variables were normalized relative to the district area, ensuring proportional comparisons across districts.

Due to inconsistencies in data availability across time, a mobile average was used to standardize temporal datasets, with the period 2017-2019 employed to examine variables such as monetary poverty, human development index, infrastructure, and monthly per capita expenditure. The 2016-2018 period focused on gross domestic product. By averaging data across these periods, two timelines were constructed for analysis, allowing for consistent variable comparisons.

Missing data was also an issue, and it was addressed by imputation to variables with fewer than 10% missing values by inserting the median values, which enabled the inclusion of more districts in subsequent spatial analysis. This imputation step was critical for increasing the number of districts available for the Local Indicators of Spatial Association (LISA) analysis, ensuring that spatial correlations could be adequately explored.

Correlation analyses were then conducted to assess relationships between socioeconomic and land use variables. Spearman correlation was selected due to its robustness in handling non-parametric data, and the correlations were visualized using the corrplot R package. This analysis enabled the identification of relationships between variables such as land use change and deforestation with socioeconomic indicators like monetary poverty, human development, and infrastructure.

In the mapping phase, ggplot2 was employed to visualize spatial distributions of the variables across the districts. This step provided a geographic context to the dataset, allowing for the identification of patterns in land use change and deforestation alongside socioeconomic conditions.

The core of the spatial analysis was the application of bivariate Local Indicators of Spatial Association (LISA) (Anselin, 1995). This technique identified spatial associations between selected socioeconomic variables—such as per capita expenditure, prevalence of stunting, human development index, and gross domestic product—and land use variables like the proportion of land deforested and areas affected by land use change. The analysis used a Queen contiguity matrix to weight district relationships, ensuring spatial proximity was accounted for. The statistical significance of spatial clusters was tested with 9,999 iterations of a pseudo-p-value test, focusing only on clusters with a p-value less than 0.01 to reduce false positives.

The data were plotted, highlighting the top five wards with the highest values for each pair of variables. These visualizations helped pinpoint areas where socioeconomic factors strongly coincided with environmental changes, thereby revealing potential hotspot districts for further investigation. This methodological framework allowed for a nuanced understanding of how land use change and deforestation correlate with social and economic factors across the Sierra and Selva regions.

5 Highlights of the correlation and LISA analysis

5.1 Correlation between land use and socioeconomic variables

The correlation between land use variables (e.g., deforestation and land use change) and socioeconomic variables (e.g., monetary poverty, human development index, monthly per capita expenditure) is weak to moderate. No correlation exceeds 0.8, and most are below 0.7, indicating that land use changes have a limited direct relationship with the analyzed socioeconomic indicators at more Amazonian level analysis (Appendix 2). However, correlations at local level revels regional correlations of socioeconomic variables (Figure 1)

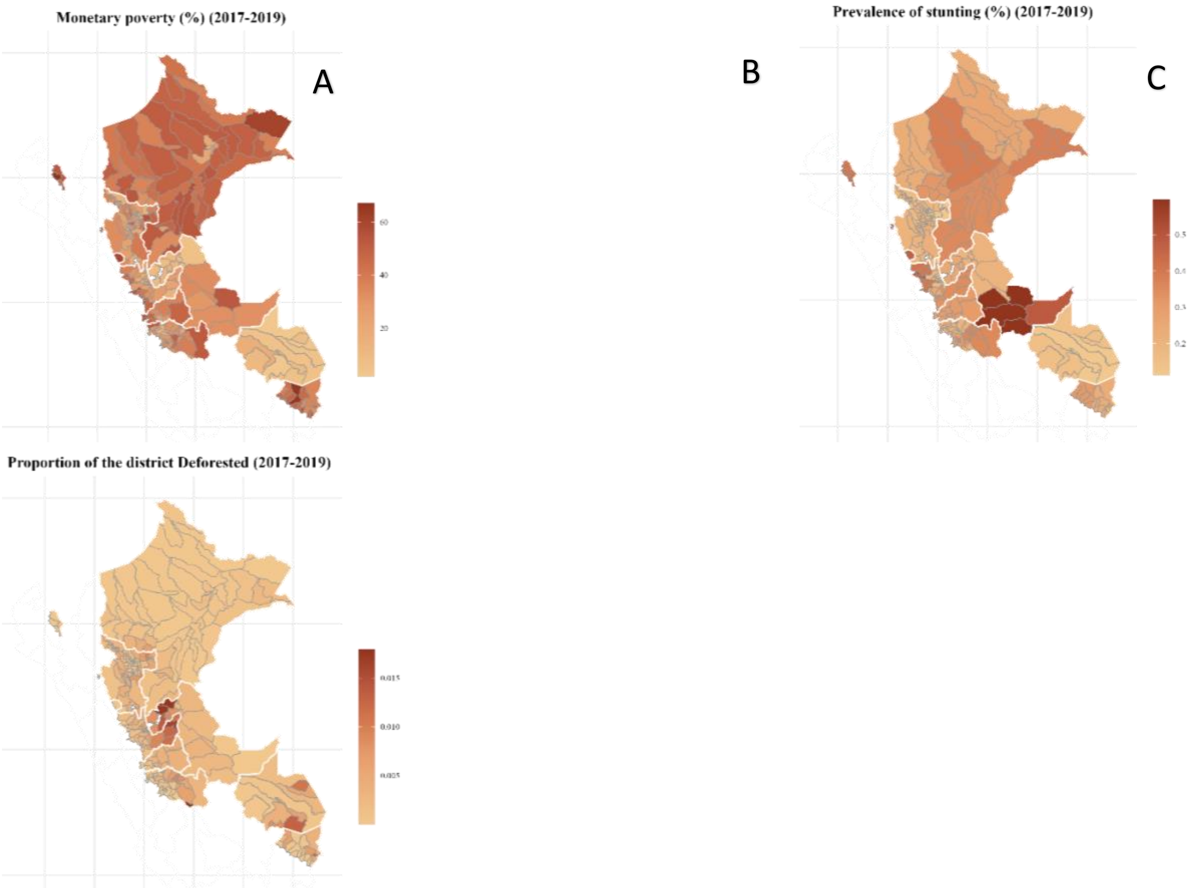

Figure 1. Selected socioeconomic variables for 252 districts in Perú for the period 2017-2019. A) Monetary poverty B) Prevalence of childhood stunting, C) Proportion of districts deforested. Districts in white did not have available data. White lines represent department boundaries.

Loreto's department reported the highest values for monetary poverty (Figure 1A). In addition, the prevalence of stunting was greater for southern Ucayali and a great portion of the Loreto department (Figure 1B). Regarding land use variables, the highest values of deforestation were in the San Martin, Ucayali, Junín, and part of the 'Madre de Dios' Department (Figure 1C).

5.2 Local Indicators of Spatial Association (LISA)

The Global Moran's I values are presented in Table 1 for the LISA analyses performed for the periods 2016-2018 and 2017-2019. The highest values for the Global Moran was found for the following relations between variables: Human Development Index and the Proportion of the district with Land use change; and the relationship between Proportion of the district with Infrastructure, with the Proportion of the district with Land use change for the period 2017-2019. Whilst the lowest value was found for the following variables: the Prevalence of stunting (%) and Proportion of the district with Land use change spatial relationship.

For the 2016-2018 period, the variables with the highest values for the Moran index were the relationship between Monthly per capita expenditure (soles) with the Proportion of the district with Land use change; and the Proportion of the district with Infrastructure with Proportion of the district with Land use change. On the other hand, Prevalence of stunting (%) and Proportion of the district with Land use change had the lowest values. Thus, it is suggested that expenditure and infrastructure can be factors affecting land use change for the 252 districts analyzed (Table 1).

Table 2. Summary of Moran´s values for the LISA analyses performed for the periods 2017-2019, and 2016-2018. Empty cells indicate that LISA analysis was not possible to perform.

Variables analyzed	Alias names	2017-2019	2016-2018
Monthly per capita expenditure (soles) - Proportion of the district with Land use change	GrealPcm_md_cambio_uso_suelo	0.228	0.225
Monthly per capita expenditure (soles) - Proportion of the district Deforested	GrealPcm_md_Def_ha	0.198	0.205
Human Development Index - Proportion of the district with Land use change	IDH_cambio_uso_suelo	0.246	
Human Development Index - Proportion of the district Deforested	IDH_Def_ha	0.162	
Proportion of the district with Infrastructure - Proportion of the district with Land use change	Infraestructura_cambio_uso_suelo	0.227	0.225
Proportion of the district with Infrastructure - Proportion of the district Deforested	Infraestructura_Def_ha	-0.019	-0.005
Monetary poverty (%) - Proportion of the district with Land use change	Pobreza_cambio_uso_suelo	-0.312	
Monetary poverty (%) - Proportion of the district Deforested	Pobreza_Def_ha	-0.268	
Prevalence of stunting (%) - Proportion of the district with Land use change	STUNTING_perc_cambio_uso_suelo	-0.395	-0.403
Prevalence of stunting (%) - Proportion of the district Deforested	STUNTING_perc_Def_ha	-0.102	-0.139
Gross domestic product (soles)- Proportion of the district with Land use change	Pbi_dist_cambio_uso_suelo		-0.032
Gross domestic product (soles) - Proportion of the district Deforested	Pbi_dist_Def_ha		0.085

LISA showed weak trends for the relationships between land use variables and socioeconomic factors. The most significant clusters were found in departments like San Martin, Ucayali, Huánuco, and Junín, with different districts showing high poverty, deforestation, and land use change.

Local Indicators of spatial association analyses were performed for socio-economic variables and land use variables (Proportion of the district Deforested) for the period 2017-2019. The spatial association between monetary poverty (%) and deforested areas was -0.268 which indicates a dispersed association trend that is weaker in the relationship between monetary poverty and deforested areas.

A total of two districts were found for the cluster of High monetary poverty and high deforested proportion of district, which were located in Ucayali department (Figure 2).

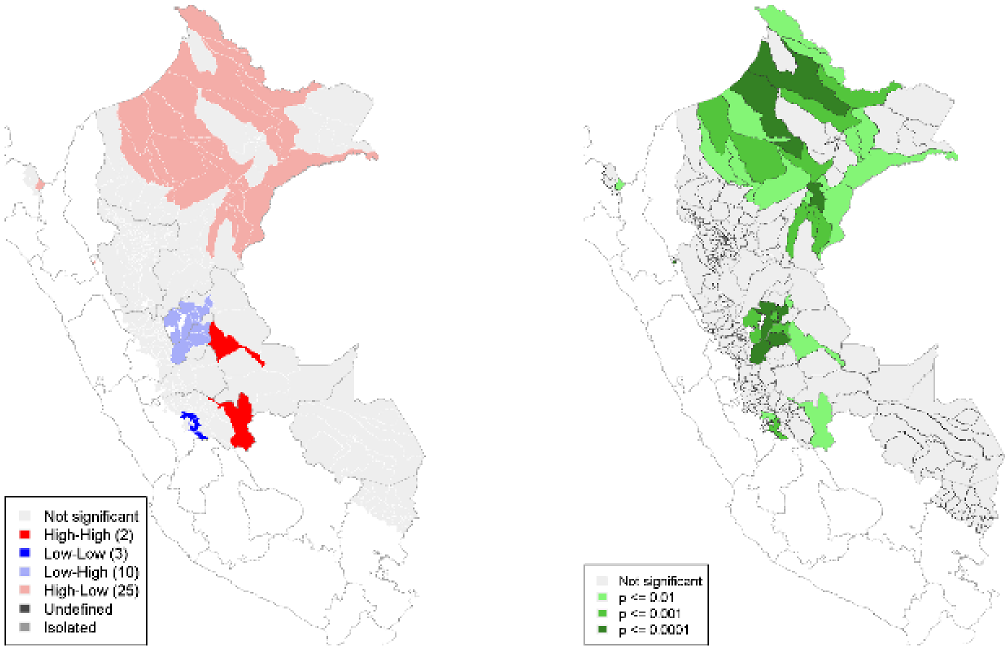

Figure 2. LISA results obtained for the relationship of monetary poverty and Proportion of the district with forest area lost.

The LISA analysis revealed notable Clusters where high land use change or high deforestation have high association with socioeconomic variables: In San Martin, six districts exhibited both high poverty and significant land use change, while Ucayali had two districts with high poverty and high deforestation. Additionally, clusters of low Human Development Index (HDI) combined with high land use change were identified in seven districts in San Martin. Four districts across Ucayali, Junín, and Huánuco showed a combination of low HDI and high deforestation, and the prevalence of stunting was notably higher in Ucayali and Huánuco.

Results obtained by the LISA analyses suggest a trend of poor socioeconomic conditions expressed in High values of Monetary poverty, the prevalence of stunting, low values of the Human Development Index, or Gross Domestic Product or Monthly expenditure in Central Perú which can explain most of the spatial clusters obtained as observed in districts for the Huánuco, Ucayali, and Junín departments where a list of districts frequently found (Supplementary table 2) is provided (A total list of all spatial clusters of interest is provided in the supplementary table 3). It is important to highlight that none of the socioeconomic variables employed had a high value of spatial autocorrelation, and the analysis limitations of this report are due to only performing analyses in districts with deforestation data available which excludes most of the southern part and coastal region of Peru.

Discussion

The goal of this analysis was to uncover potential relationships between socioeconomic conditions and environmental degradation, particularly deforestation, which is a significant driver of biodiversity loss and greenhouse gas emissions. However, the results revealed weak Spearman correlations, indicating only a marginal connection between socioeconomic indicators and land use change. Additionally, spatial autocorrelations were weak, suggesting limited clustering or geographic patterns in the relationship between these variables.

Despite these weak correlations, a set of districts mainly in the department of San Martín (16 districts out of 19), but also some in Ucayali (3 districts) and just one district in Huánuco emerged as priority areas for further investigation[1]. These districts exhibited notable patterns that warrant deeper validation, potentially serving as hotspots where socioeconomic pressures and environmental degradation intersect. The identification of these districts is critical for targeting policy interventions and conservation efforts, as they represent areas where sustainable development challenges are most acute.

Deforestation trends and the presence of oil palm plantations, to predict regions in which peatlands are likely under threat in Peru specially in Ucayali (Crnobrna et al., 2024), in Madre de Dios, artisanal-small scale gold mining (ASGM) are accelerating losses of protected forest and they are increasingly contributing to CO2 emission from both deforestation and transportation (Asner and Tupayachi, 2016; Saka et al., 2024). There are other more sustainable uses of deforested land such as cacao and coffee, especially in San Martin, but they still need long term support for a better quality of natural resource management to improve capacity to conserve forests (Pokorny et al., 2021).

Peru stands at a critical juncture in its efforts to balance economic development with environmental sustainability. The country's rich biodiversity and carbon-rich forests are invaluable global assets, yet they are under severe threat from deforestation and land use change. At the same time, poverty, malnutrition, and unequal economic growth exacerbate the challenges faced by local communities, particularly in rural areas. This research will provide a comprehensive analysis of the intersections between biodiversity loss, GHG emissions, and socioeconomic indicators, offering valuable insights for the identification of environmental hotspots. By focusing on these areas, Peru can make significant progress toward achieving its SDG targets while contributing to global efforts to combat climate change.

[1] **San Martin**: (1) Tres Unidos, (2) Tabalosos, (3) Santa Rosa, (4) Tingo De Ponasa, (5) San Pablo, (6) Zapatero, (7) Buenos Aires, (8) Huallaga, (9) Bajo Biavo, (10) Sacanche, (11) Pucacaca, (12) El eslabón, (13) Tingo De Saposoa, (14) Shapaja, (15) Cuñumbuqui, (16) Alberto Leveau; **Ucayali**: (1) Iparia, (2) Curimana, (3) Neshuya; **Huánuco**: (1) Tournavista

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7 Appendix

Appendix 1. Variables analyzed in Local Indicator of Spatial Association (LISA analyses).

Alias	Type of variable	Description	Source	Covered timeline in the tables provided by CIP	2017-2019	2016-2018
cambio_uso_suelo	Land use	Proportion of the district with Land use change	INEI	2016-2021	X	X
Def_ha*	Land use	Proportion of the district Deforested	INEI	2016-2020	X	X
Pobreza	Socioeconomic	Monetary poverty (%)	INEI	2018	X	
IDH	Socioeconomic	Human development index	INEI	2017-2019	X	
Pbi_dist	Socioeconomic	Gross domestic product (soles)	INEI	2016-2019		X
Infraestructura*	Socioeconomic	Proportion of the municipality with Infrastructure	INEI	2016-2020	X	X
GrealPcm_md*	Socioeconomic	Monthly per capita expenditure (soles)	INEI	2016-2020	X	X
STUNTING_perc*	Socioeconomic	Prevalence of stunting (%)	IHME	2016-2020	X	X

Appendix 2. Complete results of the LISA analysis performed for the present study.

Period 2017-2019

Weak to moderate correlation between land use and socioeconomic variables for 2017-2019

None of the correlations for the eight selected variables were greater than 0.8 or less than –0.8 suggesting weak to moderate correlations. None of the variables related to the Proportion of the district deforested and Proportion of the district with Land use change was greater than 0.7 excepting by Proportion of the district with Agricultural land indicating that the relationship between socioeconomic variables is weak and moderate (Figure 1). A full correlation plot with the variables extracted for the period 2017-2019 is available in Supplementary Figure 1.

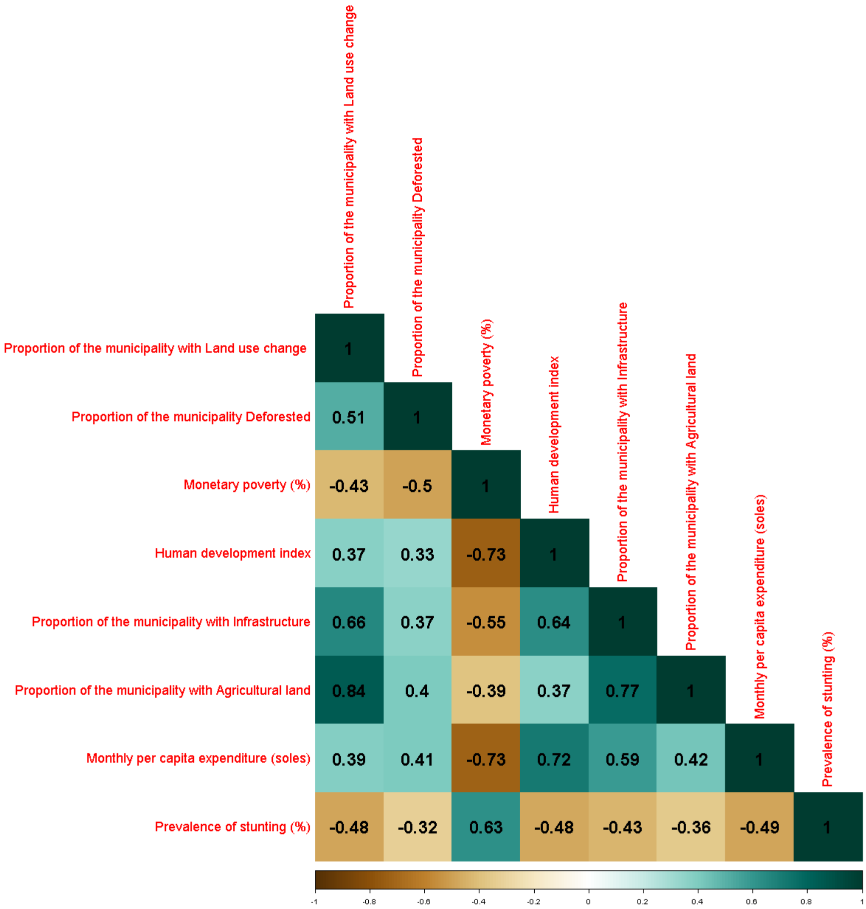

Figure 1. Spearman correlations plot for a subset of eight selected variables related to socioeconomic variables and land use variables for the period 2017-2019. Numbers represent Spearman correlation values.

Spatial distribution for socioeconomic variables and land use variables (2017-2019)

Loreto's department reported the highest values for monetary poverty and the lowest values of monthly per capita expenditure (Figure 2A & 2C). Also, Loreto has a trend to possess the lowest values for the human development index while the highest values were reported for Madre de Dios and the northern Ucayali department (Figure 2B). In addition, the prevalence of stunting was greater for southern Ucayali and a great portion of the Loreto department (Figure 2D).

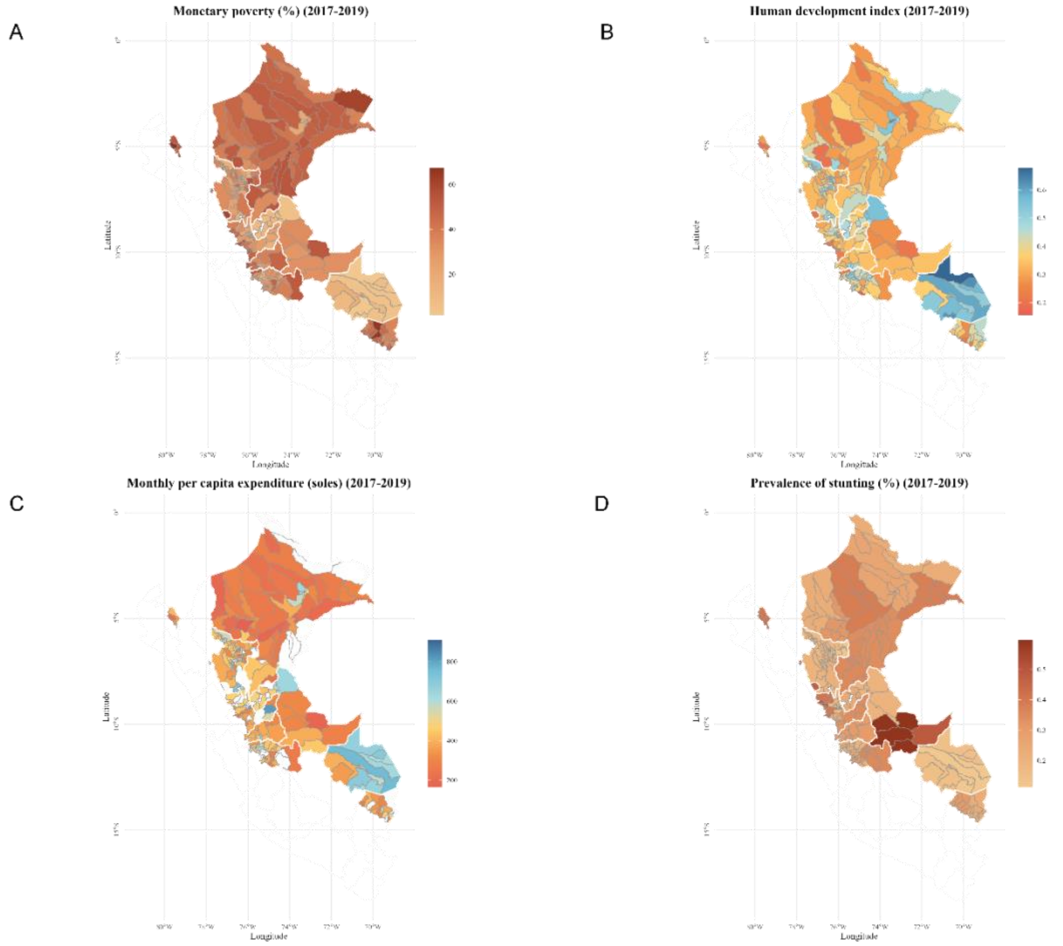

Figure 2. Selected socioeconomic variables for 252 districts in Perú for the period 2017-2019. A) Monetary poverty B) Human Development Index C) Monthly per capita expenditure, and C) Prevalence of childhood stunting. Districts in white did not have available data. White lines represent department boundaries. Images are available at https://drive.google.com/drive/folders/1S_UgjxiOMLYxiby0cREwWtGM9FWWAkfi?usp=drive_link.

Regarding land use variables, the highest values of land use change, and deforestation represented in the variables were in the San Martin, Ucayali, Junin, and north of the 'Madre de Dios' Department (Figure 3A & 3B). (Figure 3C). In contrast to the observed in the other land use variables, Ucayali has the highest values for districts with the highest proportion of districts with infrastructure (Figure 3C).

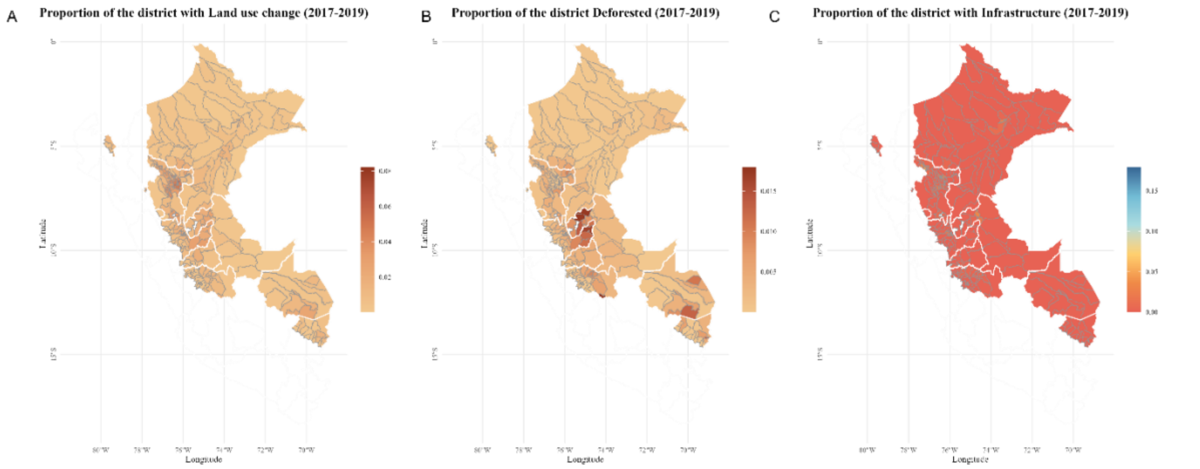

Figure 3. Land Use variables for 252 districts in Perú for the period 2017-2019. A) Proportion of the district with Land use change B) Proportion of the district Deforested C) Proportion of the district with Infrastructure. Districts in white represent not available data. White lines represent department boundaries. Images are available at https://drive.google.com/drive/folders/1S_UgjxiOMLYxiby0cREwWtGM9FWWAkfi?usp=drive_link.

Monetary poverty and land use change relationship (2017-2019)

Local Indicators of spatial association analyses were performed for socio-economic variables and land use variables (Proportion of the district with Land use change, and Proportion of the district Deforested) for the period 2017-2019. The spatial association between monetary poverty (%) and land use change, and deforested areas were –0.312, and -0.268 which indicates a dispersed association trend that is weaker in the relationship between monetary poverty and deforested areas.

A total of six districts were found for the cluster of High monetary poverty and high land use change (Figure 4A and 4B) and they were in San Martin department. On the other hand, a total of two districts were found for the cluster of High monetary poverty and high deforested proportion of district (High-High), which are in Ucayali department (Figures 4C & 4D).

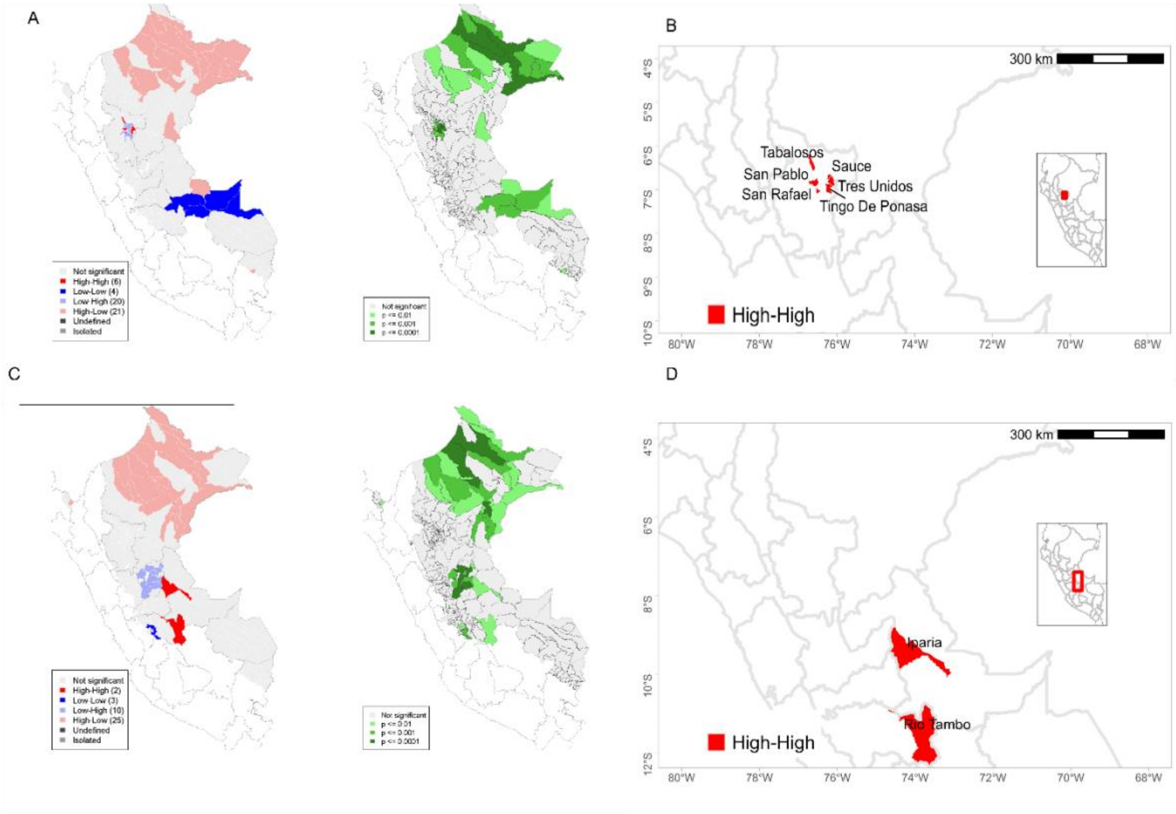

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Figure 4. LISA results obtained for the relationship of A) Monetary poverty and land use change and C) monetary poverty and Proportion of the district with forest area lost. On the right side, green colors represent the p-values supporting the districts belonging to their respective spatial clusters. B) High-High LISA cluster prioritized districts for Monetary poverty and land use change D) High-High LISA cluster prioritized districts for monetary poverty and Proportion of the district with forest area lost.

Human Development Index and land use relationship (2017-2019)

LISA analyses for the spatial relationship revealed Global Moran´s I value of 0.246 and 0.162 for the Human Development Index and land use change and deforested area respectively (Figure 5A & 5C). A total of seven districts in San Martin department were assigned to the low human development index and high land use change (Low-High cluster) (Figures 5B).

The spatial association for the human development index and the deforested area had four districts in the Low-High cluster for the Human Development Index and deforested area: Curimana, Iparia in Ucayali department, Rio Tambo in Junin, and Codo del Pozuzo in Huanuco (Figures 5C & 5D).

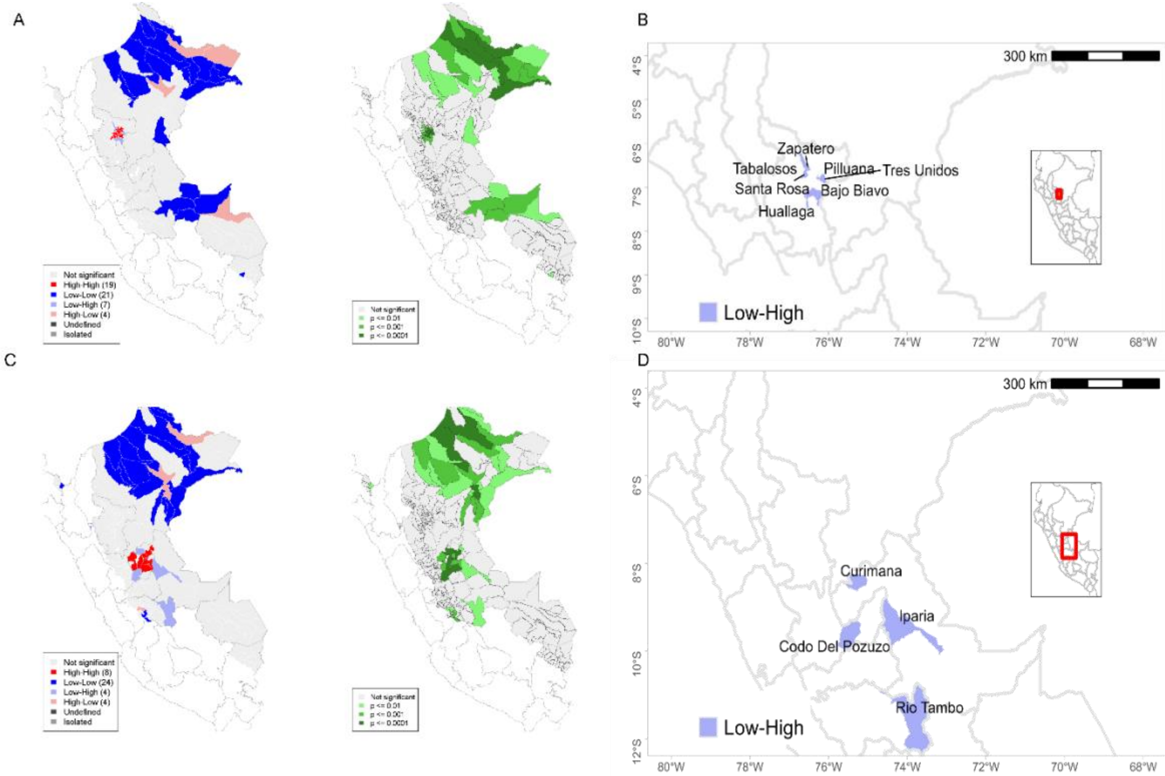

Figure 5. LISA results obtained for the relationship of A) Human Development Index and land use change and C) Human Development Index and Proportion of the district with forest area lost. On the right side, green colors represent the p-values supporting the districts belonging to their respective spatial clusters. B) Low-High LISA cluster prioritized districts for Human Development Index and land use change D) Low-High LISA cluster prioritized districts for Human Development Index and Proportion of the district with forest area lost.

Prevalence of stunting and land use relationship (2017-2019)

LISA analyses for the spatial relationship of the prevalence of stunting and land use revealed a weak spatial autocorrelation, 0.395, and -0.102 when the prevalence of stunting is associated with land use change and deforested area respectively (Figure 6). No district was assigned to the High-High cluster for the prevalence of stunting and land use change (Figure 6A). In contrast to the results obtained for land use change, the High-High cluster for the relationship between the prevalence of stunting (%) and deforestation had four districts: Tournavista, Puerto Inca, Codo del Pozuzo in Huanuco, and Rio Tambo in Junin (Figures 6C & 6D).

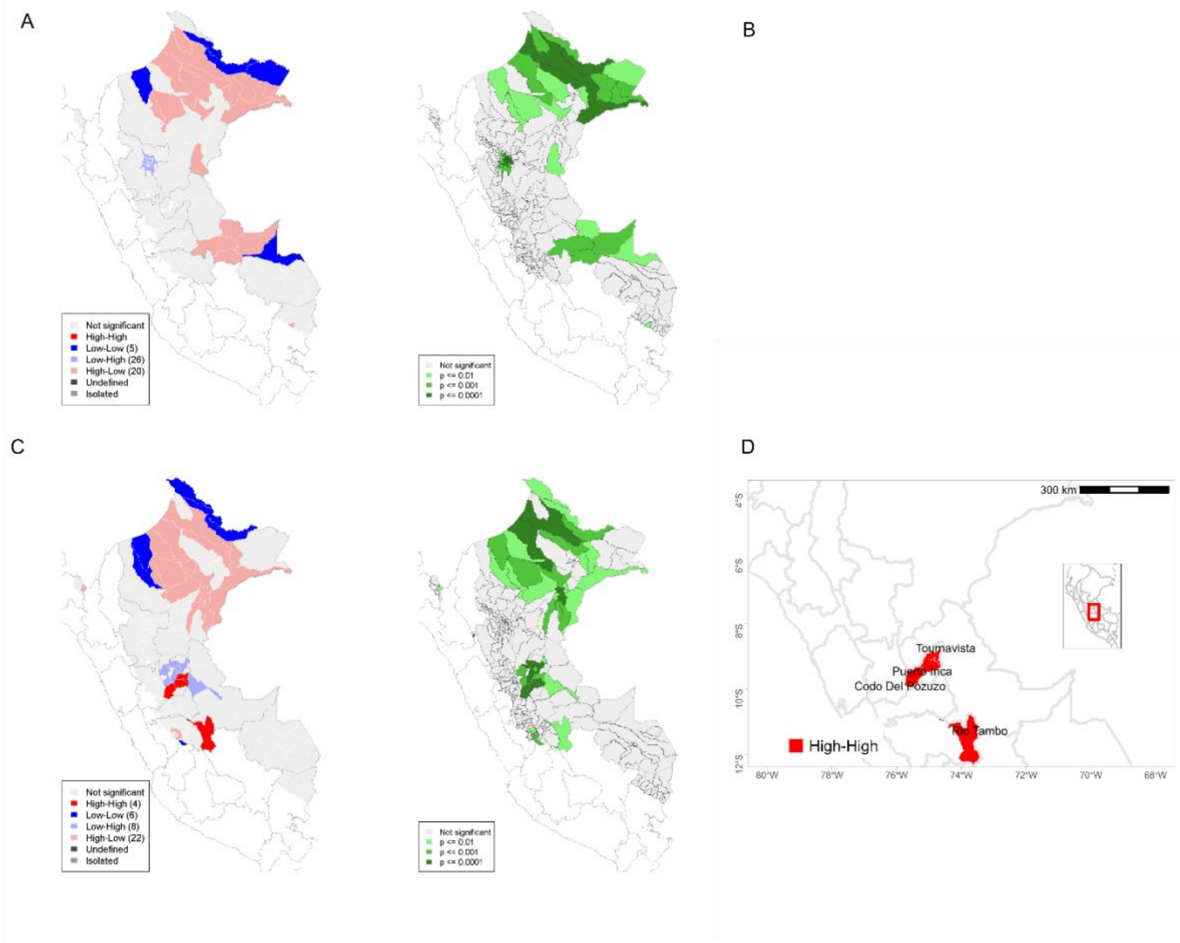

Figure 6. LISA results obtained for the relationship of A) prevalence of stunting and land use change and C) prevalence of stunting and Proportion of the district with forest area lost. On the right side, green colors represent the p-values supporting the districts belonging to their respective spatial clusters. B) High-High LISA cluster prioritized districts for prevalence of stunting and land use change. In this case, none district in High-High cluster was found D) High-High LISA cluster prioritized districts for prevalence of stunting and Proportion of the district with forest area lost.

Monthly per capita expenditure and land use relationship (2017-2019)

LISA analyses for the Monthly per capita expenditure and land use revealed a weak spatial autocorrelation (0.228, and 0.198) for the LISA performed for the Monthly per capita expenditure and land use change, and deforested area respectively (Figures 7A & 7C).

A total of eight Districts: Zapatero, Buenos Aires, Tres Unidos, Shamboyacu, Tingo de Ponasa, Pucacaca San Pablo y Santa Rosa in San Martin department for the Low-High Cluster for Monthly per capita expenditure and land use change relationship (Figure 7B). Regarding the relationship of Monthly per capita expenditure and deforestation, a total of three districts: Honoria, Tournavista and Iparia in Huanuco and Ucayali departments were assigned to the Low-High cluster (Figure 7D).

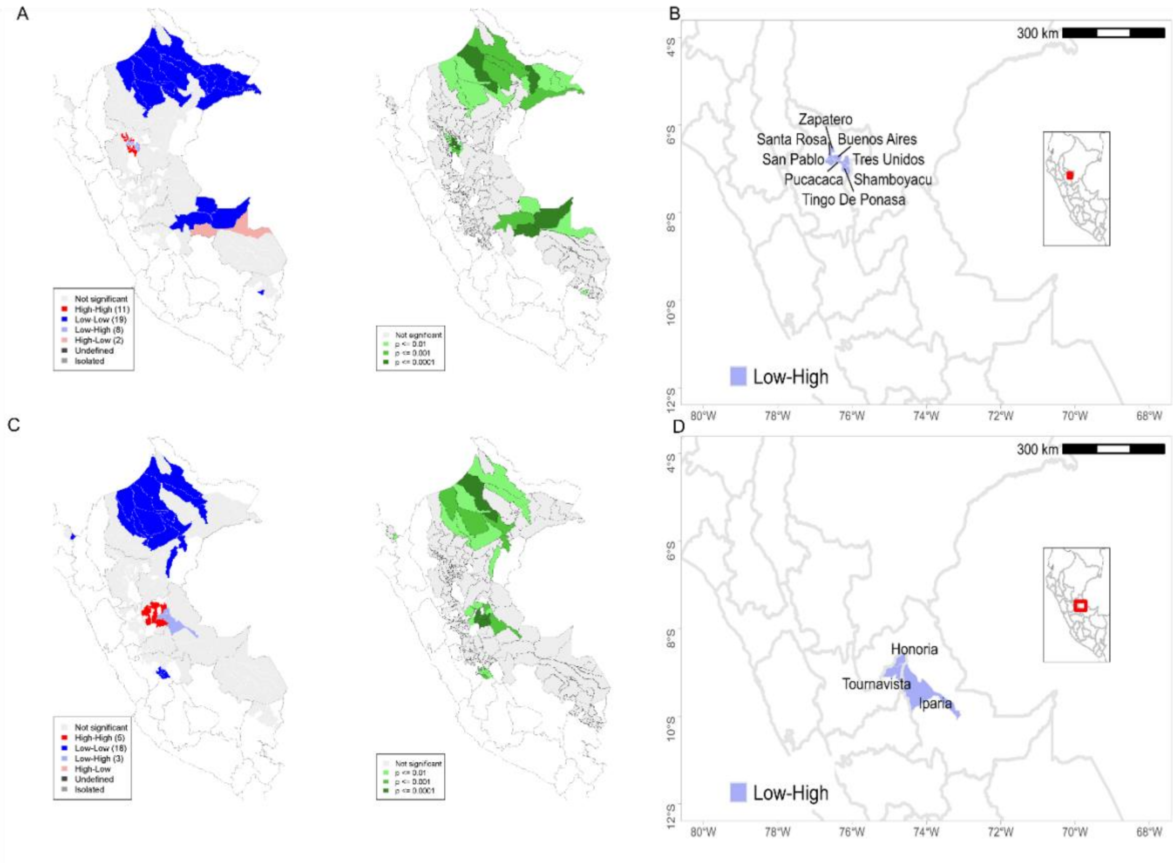

Figure 7. LISA results obtained for the relationship of A) Monthly per capita expenditure and land use change and C) Monthly per capita expenditure and Proportion of the district with forest area lost. On the right side, green colors represent the p-values supporting the districts belonging to their respective spatial clusters. B) Low-High LISA cluster prioritized districts for Monthly per capita expenditure and land use change D) Low-High LISA cluster prioritized districts for Monthly per capita expenditure and Proportion of the district with forest area lost.

Infrastructure and land use change relationship (2017-2019)

Moran's, I value for the spatial relationship of Proportion of the district with Infrastructure and Proportion of the district with Land use change, and Infrastructure and Proportion of the district Deforested were 0.227 and –0.019 respectively suggesting a dispersion trend for spatial clustering.

A total of 15 districts located in San Martin were assigned for the Low-High cluster of Proportion of the district with Infrastructure and Proportion of the district with Land use change (Figures 8A and 8B) On contrary, 10 districts in Huanuco, Junin, and Ucayali departments (Figure 8C & 8D)

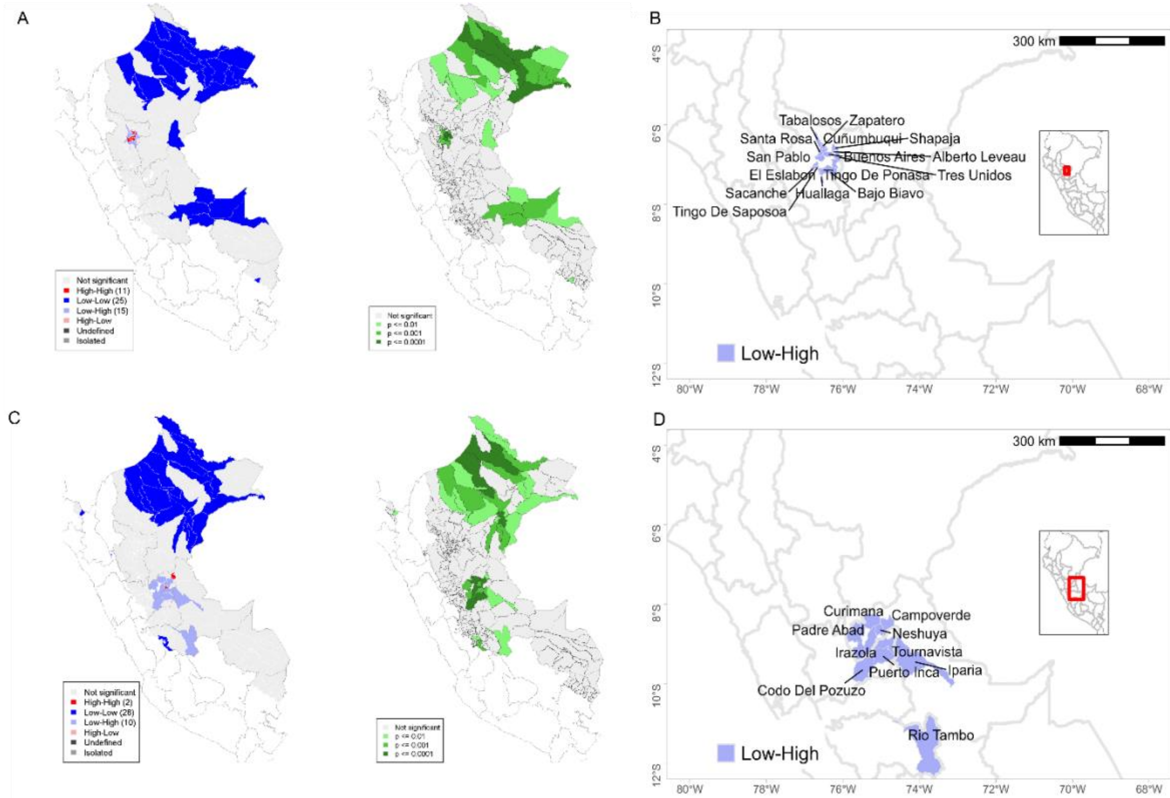

Figure 8. LISA results obtained for the relationship of A) Proportion of the district with Infrastructure and land use change and C) Proportion of the district with Infrastructure and Proportion of the district with forest area lost. On the right side, green colors represent the p-values supporting the districts belonging to their respective spatial clusters. B) Low-High LISA cluster prioritized districts for Proportion of the district with Infrastructure and land use change D) Low-High LISA cluster prioritized districts for Proportion of the district with Infrastructure and Proportion of the district with forest area lost.

Period 2016-2018

Moderate to high correlations observed for Gross Domestic product

None of the correlations for the nine selected variables were greater than 0.8 or less than –0.8 for variables and land use change variables. Only the proportion of land use change and the proportion of district with agricultural land had a high value (0.84). Also, the Gross domestic product had high values of correlation with Immigrants and emigrants. Nevertheless, the rest of the correlations suggest weak to moderate correlations (Figure 9). A full correlation plot with the variables extracted for the period 2016-2018 is available in Supplementary Figure 2.

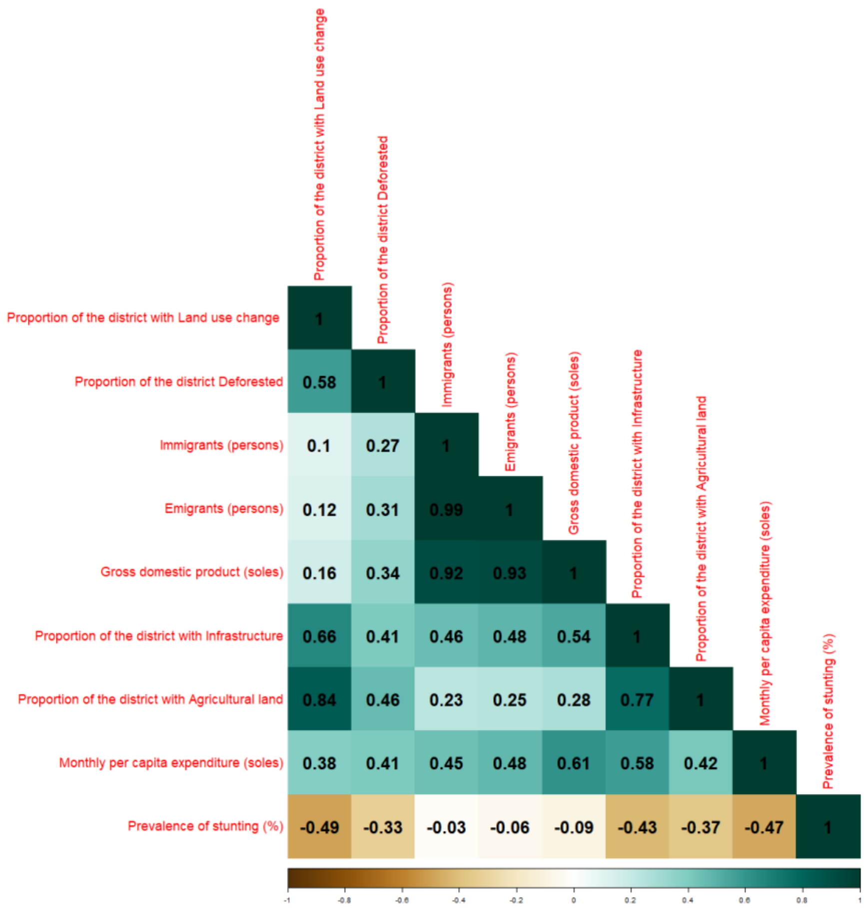

Figure 9. Spearman correlations plot for a subset of eight selected variables related to socioeconomic variables and land use variables for the period 2017-2019. Numbers represent Spearman correlation values.

A total of 25 variables were extracted for the 2016-2018 period. Only two variables were imputed: Gross domestic product and Prevalence of stunting. Moreover, the period 2016-2018 was analyzed to include in the analysis: (i) the Monthly per capita expenditure, (ii) the crime rate per 10000 inhabitants, and (iii) the Gross domestic product. Nevertheless, for further analyses, the crime rate was discarded since the data has a great number of gaps (Figure 10A).

The gross domestic product had its highest value for northern Ucayali, and Central Madre de Dios (Figure 10B). Monthly per capita expenditure possessed a similar trend as observed in the gross domestic product (Figure 10C), and the prevalence of stunting was higher in the Ucayali department (Figure10D).

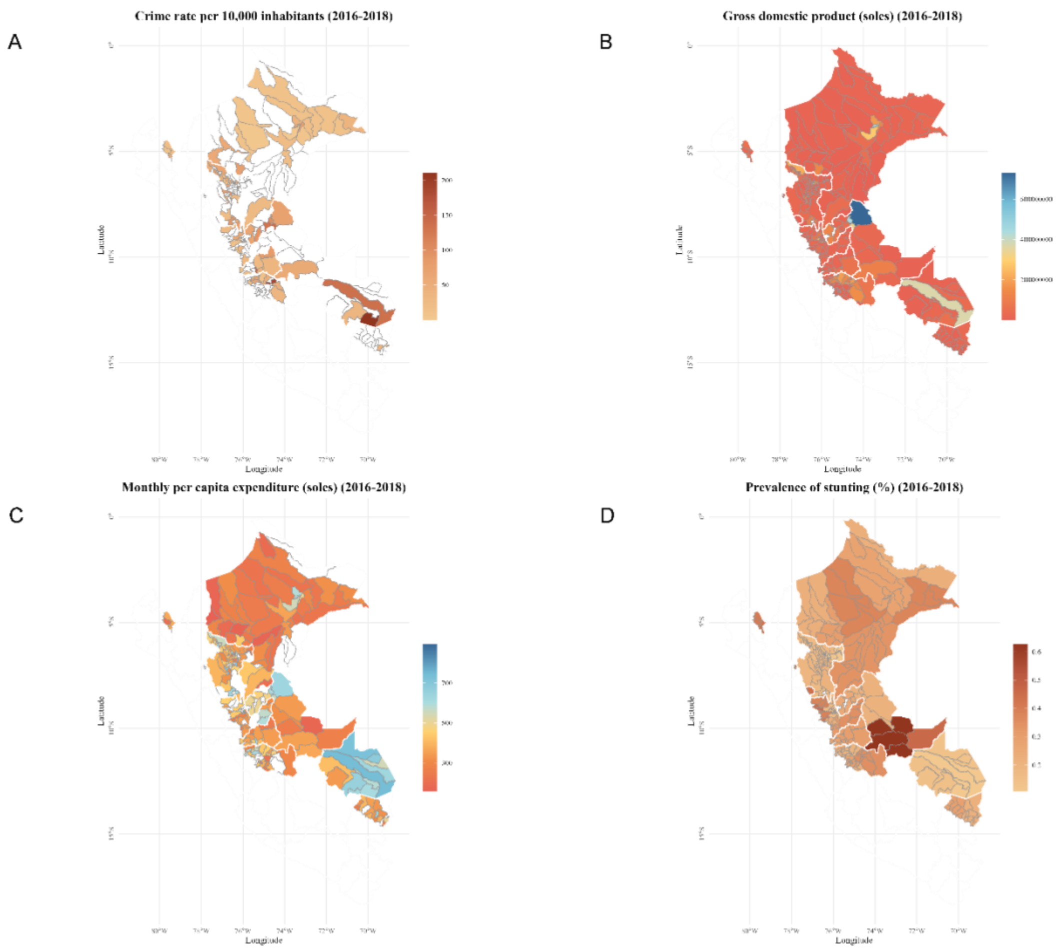

Figure 10. Socioeconomic variables maps for 252 districts in Perú for the period 2016-2018. A) Crimes per 10000 inhabitants B) Gross domestic product C) Monthly per capita expenditure D) Prevalence of stunting. Districts in white represent not available data. White lines represent department boundaries. Images are available at https://drive.google.com/drive/folders/1TuMP3yg5mhobmZGcnm9lpS1gBfQTj4yi?usp=sharing.

Regarding land use variables, the highest values for land use change were in San Martin, and Huánuco, and Madre de Dios departments (Figure 11A), the deforestation had its highest range values for the boundaries of Ucayali, Junin, Huanuco and Pasco (Figure 11B). Finally, the proportion of district with infrastructure with the highest values were found in Ucayali, and San Martin (Figure 11C).

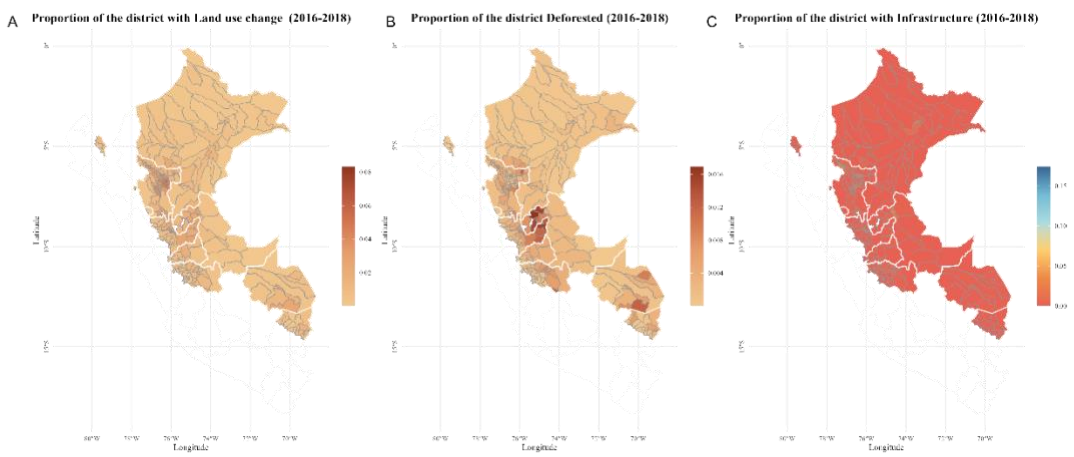

Figure 11. Land use variables maps for 252 districts in Perú for the period 2016-2018. A) Proportion of the district with Land use change B) Proportion of the district with forest area lost C) Proportion of the district with Infrastructure. Districts in white represent not available data. White lines represent department boundaries. Images are available at https://drive.google.com/drive/folders/1TuMP3yg5mhobmZGcnm9lpS1gBfQTj4yi?usp=sharing.

Gross domestic product and land use relationship for 2016-2018

LISA analyses to evaluate the Gross domestic product and land use relationship showed a dispersed spatial association of -0.032 and 0.085 for the LISA made for Gross domestic product and Proportion of the district with Land use change and Gross domestic product and Proportion of the district Deforested respectively (Figures 12A & 12C).

A total of 24 districts were found to be in the Low-High cluster, which were in San Martin department (Figure 11C). Regarding the spatial relationship between Gross domestic product and deforested area, a total of seven districts located in Ucayali, and Huanuco departments were found in the Low-High cluster (Figures 12B and 12D).

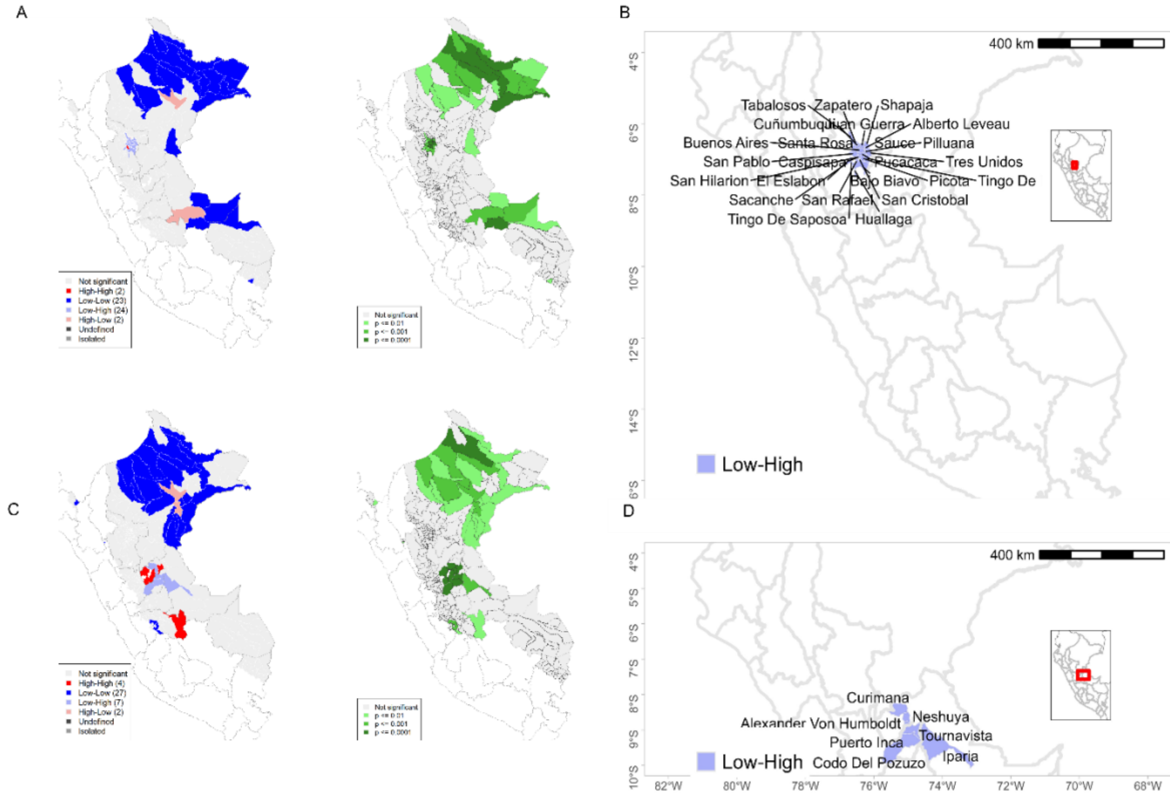

Figure 12. LISA results obtained for the relationship of A) Gross domestic product (soles) and land use change and C) Gross domestic product (soles) and Proportion of the district with forest area lost. On the right side, green colors represent the p-values supporting the districts belonging to their respective spatial clusters. B) Low-High LISA cluster prioritized districts for Gross domestic product (soles) and land use change D) Low-High LISA cluster prioritized districts for Gross domestic product (soles) and Proportion of the district with forest area lost.

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