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Research Article

Multicriteria geolocation for new urban areas: A case study in three cities of Peru

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Abstract
Urbanization, driven by the population's basic needs and regional geography, can lead to uncontrolled expansion. Therefore, multicriteria geolocation is proposed as an effective tool to identify areas that promote sustainable urban development. The objective of the research was to propose sustainable urban soils based on multicriteria soil types, focusing on the selection of three cities in Junín (Chanchamayo, Tarma and Jauja), Peru. A multicriteria analysis was employed, integrating eight edaphological criteria and the Fuzzy Logit method to manage the uncertainties inherent in geospatial data and calculate fuzzy weights to estimate the probability of urban areas. The results indicated that predominant areas, such as alluvial cones, intrusive rock hills, and extensive vegetation cover, were considered possible zones for urbanization, suggesting that the weights assigned to urbanization varied according to the edaphological criteria and their sub-criteria. The city of Tarma demonstrated notable suitability for urbanization, with 14.54% of its territory showing a probability of urbanization of 0.9; in comparison, Chanchamayo achieved a suitability of 89.22% of its territory, with a probability of urbanization of 0.75, while Jauja stood out as the city with the lowest suitability for urbanization. The application of Fuzzy logistics revealed that the probability of suitability for urbanization in Tarma, Chanchamayo, and Jauja was related to the size of the areas, showing that larger zones had a higher probability of being suitable for urban development.

Keywords: Edaphological areas, Urbanization probability, Urbanization suitability, Weights of the criteria

INTRODUCTION

Urbanization is a form of metropolitan growth that responds to complex sets of economic, social, environmental, and political forces (Kolkos *et al*., 2023; Ramadan and Effat, 2021), as well as the physical geography of an area (Kara and Akçit, 2021; van Maarseveen *et al*., 2018). Urban expansion is driven by the basic socioeconomic needs of the population (Mallick *et al*., 2022; Masoumi and Genderen, 2019; Ramadan and Effat, 2021; Weith *et al*., 2021). These needs can include industrial work activities, natural resources, and essential services such as food, water, electricity, health, education, employment, and urban residential occupancy (Al-Ghorayeb *et al*., 2023; Kolkos *et al*., 2023; MadurikaH, 2017; Ramadan and Effat, 2021). Due to urbanization, there may be a loss of natural resources and open spaces in different land uses (Al-Ghorayeb *et al*., 2023; Hossain *et al*., 2009; Ministry of Environment and Forests, 2010; van Maarseveen *et al*., 2018). In various countries around the world (e.g., Peru) (Fernandez and Schroeder, 2023), urban residential population growth is an uncontrolled expansion that can invade different land use systems (Hossain *et al*., 2009; Moradi *et al*., 2023; Puente-Sotomayor *et al*., 2021; Ramadan and Effat, 2021), such as agricultural zones, forest plantations, and silvopastoral activities (Al-Ghorayeb *et al*., 2023; MadurikaH, 2017; Weith *et al*., 2021). Understanding the spatial distribution of urban areas and the demographic behaviour of urban residents is essential for making informed land management decisions for a region (Getu and Gangadhara Bhat, 2024; Kolkos *et al*., 2023; Moradi *et al*., 2023; Weith *et al*., 2021). The suitability of urban land is a quantitative description of land use characteristics (Liladhar Rane *et al*., 2023; Masoumi and Genderen, 2019), land cover (Mallick *et al*., 2022), soil maps (Zhu *et al*., 2023), and street maps of land suitability (Moradi *et al*., 2023). This is widely used in urban land suitability mapping at the parcel level and for reclassification (Akyol *et al*., 2018; Al-Ghorayeb *et al*., 2023; Şatir, 2016).

The sustainability of land management aims to maximize land use systems that are well -adapted to the resources of a specific area (Getu and Gangadhara Bhat, 2024; Rahman and Szabó, 2022; Weith *et al*., 2021). For this reason, many countries worldwide have developed environmental regulations to control urban expansion based on current land use (Jankowski and Richard, 1994; Ministry of Environment and Forests, 2010). In different regions of Peru, there is a disorderly and uncontrolled urban growth (Comicion Permanente del Congreso de la Republica, 2002; Fernandez and Schroeder, 2023; MCVs, 2006; Ministerio del Ambiente, 2016). To mitigate this disorder, regulations such as “Land Use Planning” are being proposed (Comicion Permanente del Congreso de la Republica, 2002). This involves taking, analyzing, and studying the current land use in relation to “Economic and Ecological Zoning” (Ministerio del Ambiente, 2016). These two regulations aim to utilize land for sustainable economic development without compromising the ecological impact (Kara and Akçit, 2021; Mallick *et al*., 2022; Rahman and Szabó, 2022; Weith *et al*., 2021). They also have legal and critical functions for the compliance of regional governments in Peru (Comicion Permanente del Congreso de la Republica, 2002; Ministerio de Vivienda, Construcción y Saneamiento, 2006), managing the territory for sustainable urban development (MadurikaH, 2017; Mecca, 2023; Saha and Roy, 2021). Land Use Planning serves to strategically plan human activities for sustainable development (Ministry of Environment and Forests, 2010; Nong and Du, 2011), according to the conditions of the territory and its natural resources (Hossain *et al*., 2009; Jankowski and Richard, 1994; Jeong *et al*., 2012). Meanwhile, Economic and Ecological Zoning is a strategic tool for decision-making and prioritizing public policies that promote the sustainable management of natural resources (Ministerio del Ambiente, 2016), providing key information that stimulates public and private investment (Fernandez and Schroeder, 2023). Unfortunately, officials in regional governments have not adhered to the mandates of these land management documents due to the complexity of studying the dynamic land use process, which involves both economic and political aspects.

To address these issues, many countries around the world have sought evaluation methods for land management using multiple land use criteria while reducing the economic and legal-political aspects (Gelan, 2021; Weith *et al*., 2021), among which is the Geographic Information System (GIS) (Al-Ghorayeb *et al*., 2023; Kolkos *et al*., 2023; Moradi *et al*., 2023). To date, GIS and Multicriteria Analysis (MCA) serve the purpose of designing, capturing, storing, manipulating, analyzing, managing, and presenting spatial or geographic data (Ahmed and Kilic, 2016; Chan *et al*., 2012; Şatir, 2016). The application of GIS allows users to create interactive queries (Akyol *et al*., 2018; Criado *et al*., 2017; Jeong *et al*., 2012; Madurika H, 2017), analyze spatial information, edit data on maps, and present the results of all these operations (Masoumi and Genderen, 2019; Ramadan and Effat, 2021; Saha and Roy, 2021). For example, land cover can be determined through field studies or remote sensing data (Gelan, 2021; Mecca, 2023; Rahman and Szabó, 2022). The urban land environment represents one of the most challenging areas for remote sensing analysis due to the high spatial and spectral diversity of surface materials (Al-Ghorayeb *et al*., 2023; Kolkos *et al*., 2023; Moradi *et al*., 2023). Additionally, designing geospatial databases within a GIS environment is crucial for developing support systems for land planning (Kara and Akçit, 2021; Karimimoshaver *et al*., 2020; Liladhar Rane *et al*., 2023; Mallick *et al*., 2022). Meanwhile, Multicriteria Analysis (MCA) is a decision-making methodology used to evaluate and compare alternative options based on multiple criteria or factors (Getu and Gangadhara Bhat, 2024; Puente-Sotomayor *et al*., 2021; Zhu *et al*., 2023). The multicriteria analysis for geolocating new construction areas involves identifying criteria that encompass the physical (Rahman and Szabó, 2022), mechanical (Weith *et al*., 2021), and geotechnical properties of the soil (Akyol *et al*., 2018), as well as the basic needs for urbanization (Luo *et al*., 2019; Nahib *et al*., 2018). By employing GIS-based MCA (Moradi *et al*., 2023), potential construction sites can be systematically evaluated (Mallick *et al*., 2022), taking into account a wide range of soil properties (Zhu *et al*., 2023), which facilitates the selection of optimal locations for building houses and structures (Rahman and Szabó, 2022). Therefore, the objective of the research was to propose sustainable urban soils based on a multicriteria analysis of soil types in three cities in Peru.

MATERIALS AND METHODS

Study area

The three provinces of Junín (Peru) were chosen due to their potential projections for socioeconomic development in urban demographic growth, agriculture, mining, forestry, and livestock (Fig. 1). The three provinces were: Chanchamayo (Geographically located in the high jungle ecological floor of the Junín region, its provincial altitude varies from 500 to 1930 m.a.s.l., covering an area of 4,676.86 km², with a length of 395.92 km, a total population of 167,060 inhabitants, and a density of 32.01 inhabitants/km²). Tarma (Geographically located in the Andean-Amazonian mountains and jungle, ranging from 4,000 m.a.s.l. (cold land or Suni and Quechua) to 1,400 m.a.s.l. (temperate land or Yunga). It has an area of 2,670.58 km² and a total length of 350.19 km, a total population of 111,097 inhabitants, and a density of 32.59 inhabitants/km². It is home to the Pampa Hermosa National Sanctuary. Jauja (Geographically located in the central Andes, the topographic map shows a minimum altitude of 3,773 m.a.s.l. and a maximum altitude of 4,562 m.a.s.l., covering an area of 749.19 km² with a total area of 4,354.19 km², a surface area of 467.83 km², a total population of 86,213 inhabitants, and a density of 1,773.07 inhabitants/km²).

Integration of multicriteria data

The intersection of layers in a GIS was used as a key technique to assess the suitability of areas for urban development (Getu and Gangadhara Bhat, 2024; Liladhar Rane *et al*., 2023; Mecca, 2023), integrating eight criteria: geomorphology, current land use, land use capacity, physiography, geology, economic and ecological zoning, soil texture, and soil depth (Fig. 2). This methodology allowed for the combination of multiple factors in a single spatial analysis (Al-Ghorayeb *et al*., 2023; Moradi *et al*., 2023; Zhu *et al*., 2023), identifying areas that simultaneously meet all the necessary requirements for urban use, thereby optimizing land planning and avoiding isolated analyses of each criterion (Kolkos *et al*., 2023; Mallick *et al*., 2022; Rahman and Szabó, 2022).

Fuzzy logit multicriteria analysis

The Fuzzy Logit method was used for multicriteria geolocation to identify and select new urban soil areas

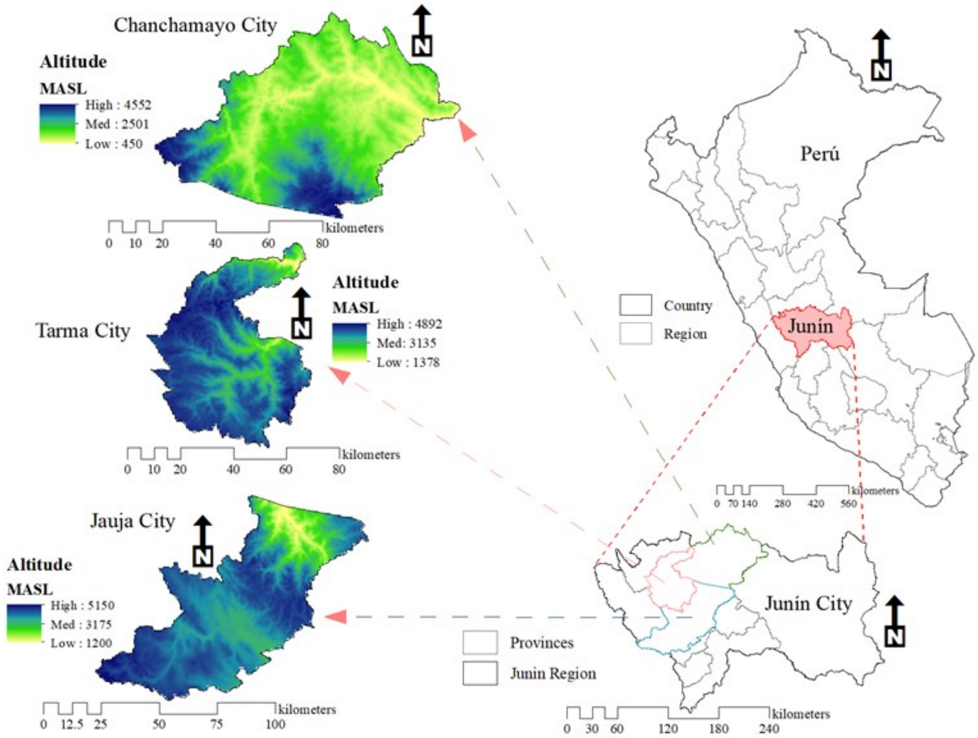

Fig. 1. *Location of the three cities of the Junín region*

(Mecca, 2023). This approach allowed for managing inherent uncertainties in geospatial data and evaluation criteria (Zhu *et al.*, 2023). The following model was applied for the weighting of each criterion and sub-criterion:

$$W_i = \frac{1}{1+e^{-x_i}} \quad \text{Eq. 1}$$

For each criterion i, a fuzzy weight Wi is obtained using the logistic function, which assigns values in the range of 0 to 1 (Chang, 1996). Here, xi is the value corresponding to criterion i, which could be based on measurements, classifications, or expert assessments on the ground (Moradi *et al.*, 2023). Fuzzy Logit Operators: To combine the different geotopographic criteria into a single decision, fuzzy logic operators were used:
AND (x, y) = min (x, y) → It was used to represent the intersection of two conditions.
OR (x, y) = max (x, y) → It is used to represent the union of two conditions.
NOT(x) = 1-x → The complement of x represents the negation of a condition.
Fuzzy Logit Model: Once the fuzzy weights for each criterion were calculated, they were integrated into a logistic regression model, known as the Logit model, to estimate the probability of urbanization (Kara and Akçit, 2021).

$$P[y=1] = \frac{e^{\beta_0+\beta_1 W_{Sd}+\beta_2 W_{Ph}+\cdots+\beta_8 W_{EEZ}}}{1+e^{\beta_0+\beta_1 W_{Sd}+\beta_2 W_{Ph}+\cdots+\beta_8 W_{EEZ}}} \quad \text{Eq. 2}$$

Where: $P(y{=}1)$ is the probability of the area being suitable for urbanization. $\beta 0$ is the intercept term. β_1, β_2, … , β_8 are the coefficients that represent the influence of each criterion on the decision. W_{Sd}, W_{Ph}, … , W_{EZZ} are the fuzzy weights assigned to each criterion. If $P(y=1)$ is close to 1, it indicates that the land is highly suitable for urbanization; if $P(y=1)$ is close to 0, the land is poorly suitable.

RESULTS

Analysis of criteria and sub-criteria for edaphological areas

In the city of Tarma, it was identified that the predominant geomorphology consisted of alluvial fan areas, with extensions of 294.43 km², 246.71 km², and 199.48 km², as well as hills on intrusive rock reaching 283.18 km² and 256.21 km². Regarding land use, urban and governmental zones occupied 6.61 km², while land designated for extensive crops totalled 83.21 km². Tarma exhibited very steep slopes (>75%), which limited urbanization. The predominant soil texture was loam, covering an area of 32.89 km². In terms of suitability for use, it was determined that the areas suitable for urbanization were 6.60 km², and the lands suitable for pasture encompassed 46.86 km².

In Chanchamayo, despite having a smaller area of alluvial fan, with records of 7.85 km² and 1.41 km², the hills on intrusive rock reached 26.04 km². In terms of land use, an urban and governmental area of 12.59 km² was identified, while forested lands totalled 184.55 km². The areas of the city of Chanchamayo had predominant slopes greater than 75%, with textures that included various combinations. Regarding suitability for use, an urban area of 12.58 km² was found, and the lands suitable for low-quality agroecological clean crops covered 112.88 km².

In Jauja, the alluvial fan covered an area of 7.45 km², while the hills on intrusive rock were significant, reaching 90.10 km². It was reported that urban areas occupied 6.24 km², and forest coverage was high, totalling up to 248.12 km². Jauja exhibited very steep slopes (>75%) that limited urbanization, although flat areas were also found, offering opportunities. In terms of land suitability, an urban area of 6.24 km² was identified, along with lagoons occupying 46.57 km² (Fig. 3).

Estimation of weights of the criteria based on their areas

Geomorphology (Ge) had a varied impact across the three cities. In Tarma, the relationship between geomorphology and area was moderate, with a weight of 0.0032, indicating that the land was relatively suitable for urbanization. In Chanchamayo, this value was lower, reflecting fewer development opportunities, whereas in Jauja, the influence was more significant, with a weight of 0.0051, indicating more favourable topographical characteristics for urban expansion. Regarding current land use (Clu), Tarma showed a greater availability

Table 1. Area distribution by urbanization probability according to the fuzzy logit model

Fuzzy logit P [y=1]	Tarma city [Area km^2]	Chanchamayo city [Area km^2]	Jauja city [Area km^2]
0	238.40	368.79	2888.85
0.25	0	0	0
0.5	21.90	12.31	24.89
0.75	2022.11	4134.42	1356.90
0.9	388.17	118.18	82.93
Total	2670.58	4633.71	4353.57

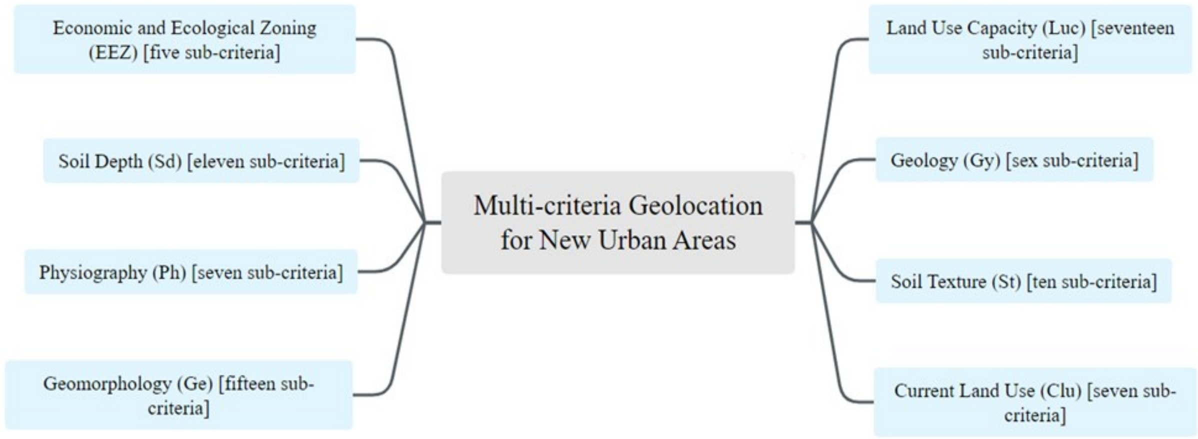

Fig. 2. *Schematic representation of the Integration of Multicriteria data*

of land with a weight of 0.0149, compared to Chanchamayo (0.0114) and Jauja (0.0066), which exhibited a balance between urban and agricultural areas but with less potential. Land use capacity (Luc) also varied; in Tarma and Jauja, the weight was 0.0028, reflecting a limited capacity for urban uses, while in Chanchamayo, this value was even lower. Finally, physiography (Ph) had a weight of 0.0053 in Jauja, indicating a considerable influence on the suitability of the land for urbanization, followed by Chanchamayo (0.0045) and Tarma (0.0018), which presented fewer physiographic restrictions, favoring urban development (Fig. 4).

Geological formations (Gy) in Tarma and Jauja limited urban potential, with weights of 0.0044 and 0.0078, respectively. Chanchamayo exhibited the highest geological influence (0.0082), due to volcanic and sedimentary lands that affected stability and urbanization possibilities. In economic and ecological zoning (EEZ), Chanchamayo also had the highest weight (0.0147), indicating areas that are more productive and conservation-oriented, which limits urban development. With a weight of 0.0035, Tarma allowed for greater flexibility, while Jauja, with a weight of 0.0068, showed a balance between productive and conservation areas. The soil texture (St) in Tarma was 0.0028, reflecting moderately suitable soils for construction, while in Chanchamayo, it was higher (0.0057), suggesting better suitability for urbanization. In Jauja, with a weight of 0.0053, both favourable and unfavourable textures were identified. Finally, soil depth (Sd) was similar in the three provinces. Tarma showed a weight of 0.0028, indicating moderate depth that favoured urban development. In contrast, Chanchamayo and Jauja, with weights of 0.0053 and 0.0057, respectively, presented deep soils that facilitated urbanization, albeit with restrictions due to the presence of shallow or rocky soils.

Probability of multicriteria geolocation based on area

In Tarma, evaluating 2,670.58 km², it was demonstrated that 75.72% of the area had high suitability, with 388.17 km² identified with an urbanization probability of 0.9. Although 8.93% of the total area had an urbanization probability of 0, this does not diminish the considerable area that is favourable for urban development. The Fuzzy Logit model calculated the probability of urbanization as P[y=Area probability] = 0.0012.Tarma City [Area]+0.6004, presenting a coefficient of determination R^2 = 0.0001 and a correlation value r=0.0117. Although the t-test yielded a value of 0.7421, which is below the critical threshold of 1.9600, the research confirmed that most areas in Tarma have a considerable capacity for urban development (Fig. 5).

In Chanchamayo, evaluating 4,633.71 km², 89.22% was classified in the 0.75 category, indicating high suitability for urbanization. Specifically, 118.18 km² showed a probability of 0.9, supporting its viability for urban development. Although 7.96% of the total area exhibited an urbanization probability of 0, indicating less suitable portions, this does not overshadow the areas with favorable conditions. The probability equation was established as P[y=Area probability] = 0.0004. Chanchamayo City [Area]+0.5621, with an R^2 of 0.0005 and a correlation coefficient r of 0.0228, which should be interpreted cautiously. The t-student test yielded 0.9885, below the critical threshold of 1.9600, but does not diminish the feasibility of urbanization in much of the analyzed area (Table 1).

In Jauja, evaluating 4,353.57 km², 31.17% was classified with an urbanization probability of 0.75, indicating moderate suitability for urban development, and 82.93 km² presented a probability of 0.9, reaffirming its viability for the construction of new housing. Although 66.36% of the territory was categorized with a probability of 0, indicating limitations in those areas, this does not detract from the development potential in other regions. The probability equation was established as P [y=Area probability] = 0.0007.Jauja City [Area] + 0.2083, with an R^2 of 6E-05 and a correlation coefficient r of 0.0077, suggesting a weak relationship be-

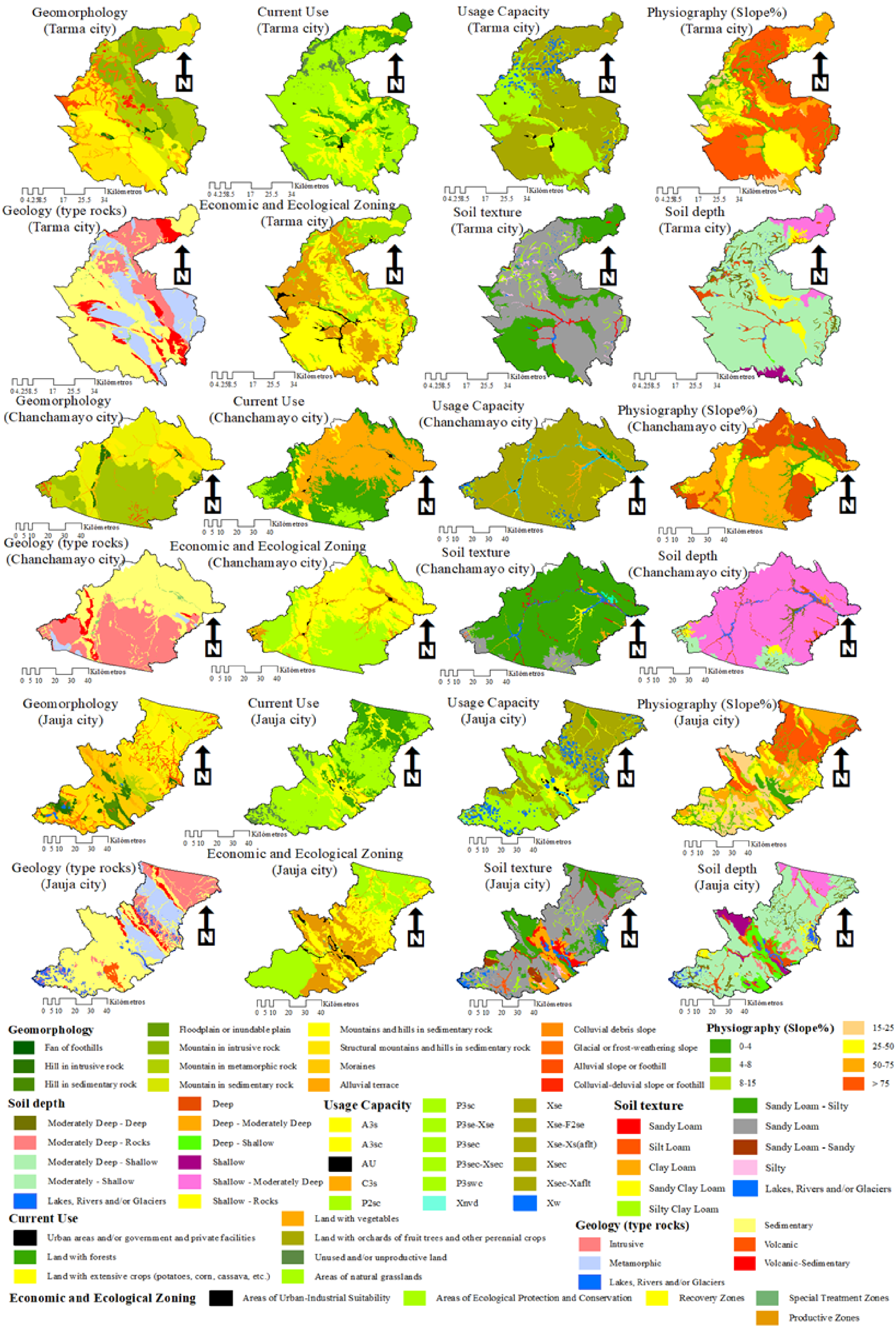

Fig. 3. *Analysis of criteria and sub-criteria for types of edaphological surfaces*

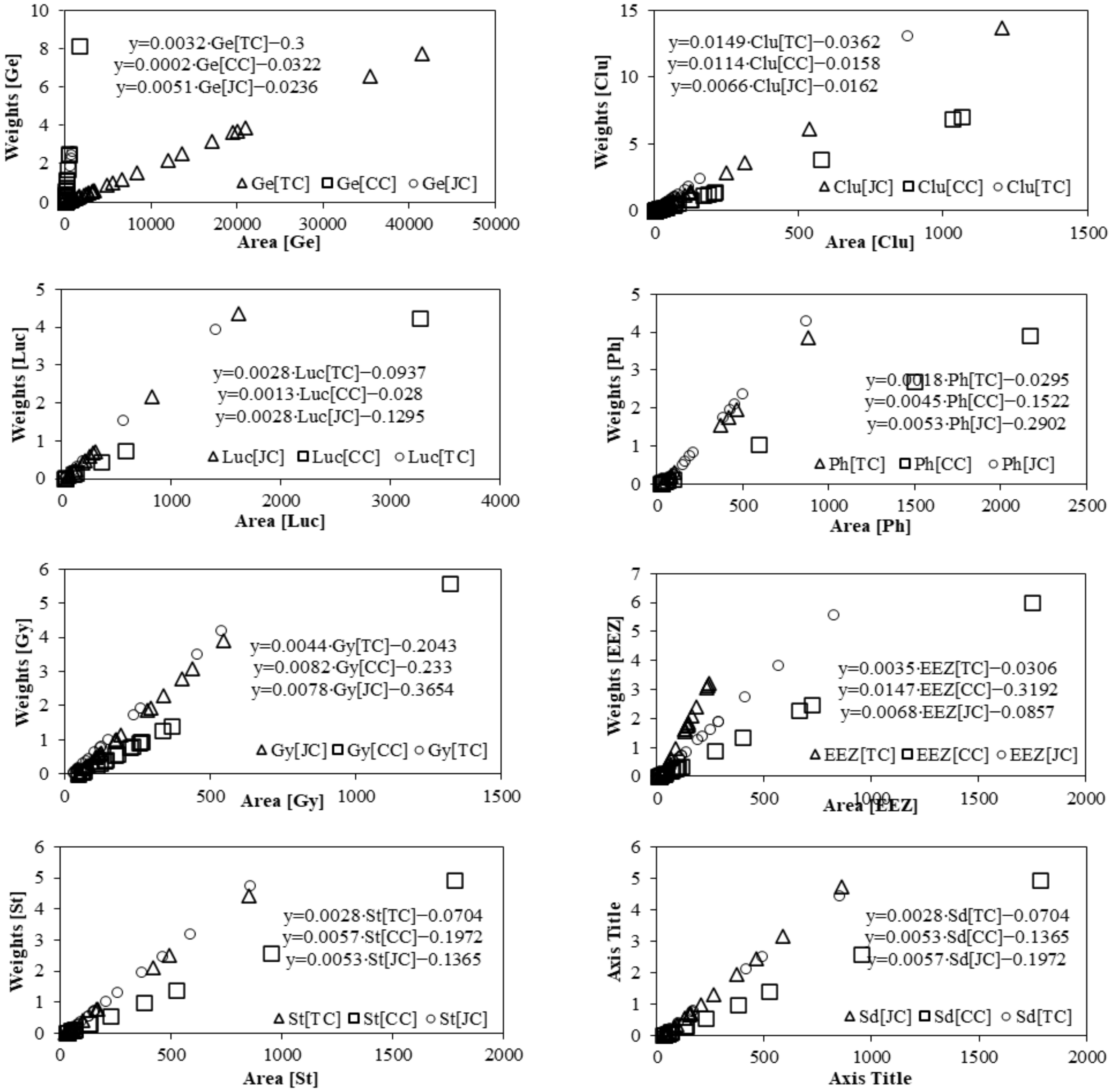

Fig. 4. *Regression of edaphological areas for weight estimation*

tween the analyzed surface and the probability of urbanization. However, the existence of high- suitability areas reinforces urban development's viability. The t-test resulted in a p-value of 0.5454, which is below the critical threshold of 0.05, but the data do not undermine the growth potential in the identified areas.

Multicriteria geolocation as a function of area probability

The logistic regression model applied (Fig. 5D), which utilized a sigmoid function Wi = 1/(1 + e^-xi), demonstrated the relationship between the size of the areas and their probability of being suitable for urbanization. The non-linear pattern indicated that smaller areas had a lower likelihood of suitability, with the probability increasing steeply as the area size grew before stabilizing at a high probability level. This behaviour, consistent with the logistic growth curve, suggests that larger areas in the analyzed cities were more likely to be deemed suitable for urban expansion.

The analysis of urbanization suitability across Tarma, Chanchamayo, and Jauja was conducted using a probabilistic model, as represented in Fig. 6, where different areas were classified into colour-coded categories based on their likelihood of being suitable for urban development. Tarma and Chanchamayo had significant portions of their areas classified as highly suitable (light green and dark green), with Chanchamayo showing the highest overall probability for urban expansion. Jauja, in contrast, had a much larger proportion of land in the low-suitability category (red), indicating limited potential for urban growth (Fig. 6).

The probability of areas suitable for urbanization was categorized into five levels, ranging from very low

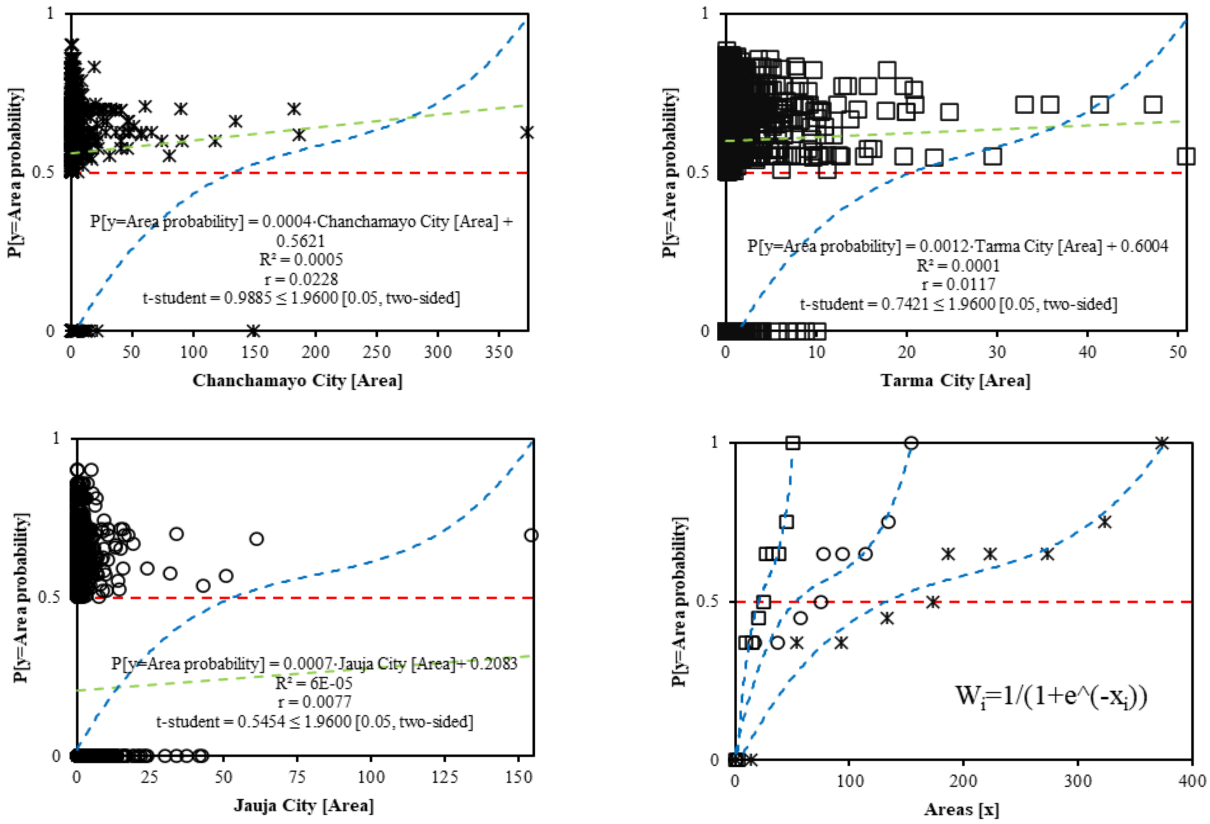

Fig. 5. *Probabilistic multicriteria analysis "Fuzzy Logit Model" for Area*

(0.00) to very high (0.99), and depicted by different colours on the map. Chanchamayo had the largest portion of its land classified as highly suitable (green areas), with 89.22% of the city showing a high probability of urbanization (0.75–0.99 range), while Jauja had a majority of its area classified as unsuitable for urbanization (66.36% in red). Tarma exhibited a more balanced distribution, with notable areas of high suitability (14.54% in the 0.99 range).

This methodology identified critical areas for potential urban growth, highlighting the high suitability of Chanchamayo compared to the more limited potential of Jauja. The use of advanced statistical modelling, combined with geographic and geomorphological data, provided a clear understanding of the urbanization potential across the three cities, highlighting the importance of considering area size and land characteristics when planning future urban development.

DISCUSSION

Analysis of soil condition area criteria and sub-criteria

The analysis of criteria and sub-criteria for edaphological areas revealed that both in the three analyzed Peruvian cities and in other studies, critical factors influencing urban development were identified, although the criteria vary according to regional contexts. In Tarma, Chanchamayo, and Jauja, edaphological variables such as soil texture, depth, and land use capability were highlighted as key sub-criteria affecting urban planning decisions. By integrating these criteria, a solid foundation was established to assess the suitability of urban areas based on their edaphological attributes.

These findings align with Gelan (2021), conducted in Sululta, Ethiopia, which emphasizes the importance of understanding local environmental conditions when planning urban expansion. These factors were crucial for geolocating new areas in three Peruvian cities. Similarly, the research by Rahman and Szabó, (2022) in Rajshahi, Bangladesh, indicates that physical characteristics, such as land cover, road networks, and elevation, are essential in determining land suitability for residential use. These aspects were also significant, although road networks were not considered for the three Peruvian cities.

Likewise, the study by Al-Ghorayeb *et al.,* (2023), analyzing land suitability for the city of Nabatiyeh in Lebanon, highlights factors such as slope and proximity to urban areas. These aspects, along with soil-related factors, were crucial in assessing potential expansion zones in the three Peruvian cities. Additionally, the research by Ramadan and Effat (2021) in Ismailia, Egypt, and Getu and Gangadhara Bhat (2024) in Bahir Dar, Ethiopia, underscores that effective urban planning must consider soil characteristics as vital indicators of land suitability, as well as proximity factors such as roads and airports, to analyze urban growth sustaina-

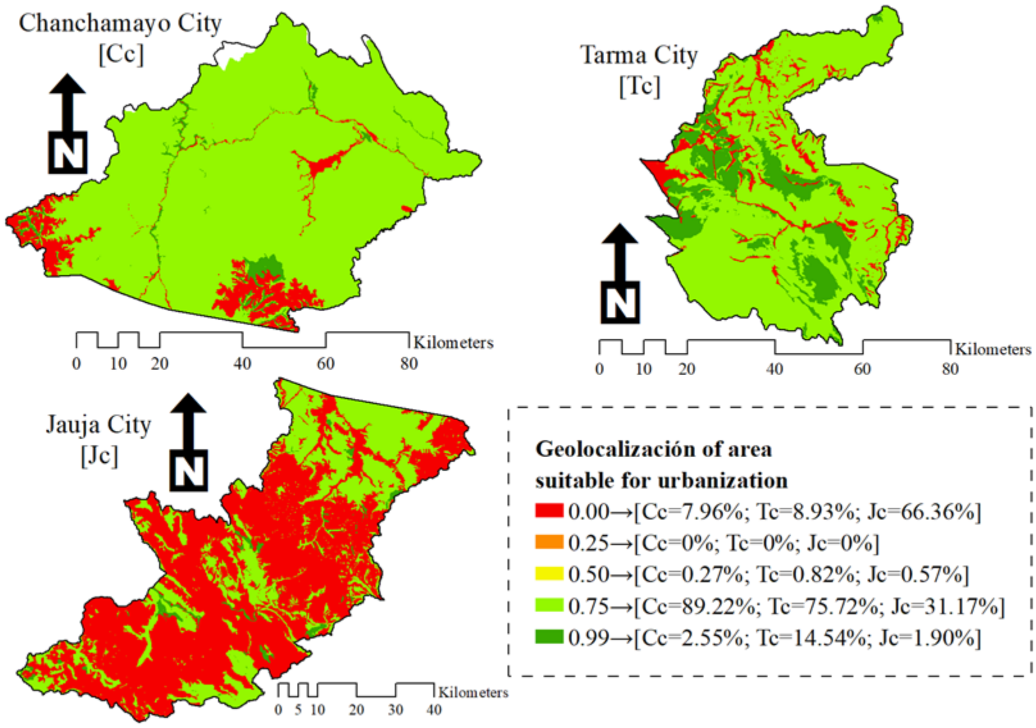

Fig. 6. *Probabilistic multicriteria geolocation and percentage of surface area allocated*

bly. Thus, it was confirmed that soil characteristics, in conjunction with accessibility and infrastructure, constitute convergent criteria for urban development, a trend also observed in the three Peruvian cities.

Estimation of weights of the criteria according to their areas

Estimating weights for edaphological criteria in the three cities of Junín using Fuzzy Logic Multicriteria Analysis was essential for determining the suitability of different areas for urban development. This finding aligns with the methodology of Kara and Akçit, (2021) in Trikomo, Cyprus, who emphasize that land suitability assessments should prioritize criteria that significantly affect the sustainable use of resources. Furthermore, the estimated weights for the edaphological criteria in the three Peruvian cities were consistent with the methodologies of Zhu *et al.,* (2023) in Songyuan City, China, who used multicriteria decision-making techniques to determine the importance of various environmental factors in urban planning.

Meanwhile, the study by Al-Ghorayeb et al. (2023) used the Analytic Hierarchy Process (AHP) to assign importance to each criterion. Rahman and Szabó, (2022) applied AHP to calculate the weights of socio-environmental factors, highlighting the need to balance sustainability with economic development. Similarly, Liladhar Rane *et al.,* (2023) in Nashik, India, employed multi-influence factors (MIF) – a similar approach that assigns weights to geo-environmental, geophysical, and socioeconomic factors – focusing on site suitability for sustainable urban settlements. Although the different methods applied by Al-Ghorayeb *et al*. (2023) ; Liladhar Rane *et al*. (2023) ; Rahman and Szabó, (2022) were essential in concluding that soil characteristics—such as depth and land-use capability—carried significant weight due to their direct impact on urban development potential in the three Peruvian cities.

Although the research by Fernandez and Schroeder, (2023) in Piura, Peru, did not explicitly mention the use of AHP (Analytic Hierarchy Process) or Fuzzy Logic Multicriteria Analysis, it did highlight the importance of data layers and thematic variables in urban planning. Clearly, these data were critical for the three Peruvian cities, as they aligned with weight estimation based on edaphological characteristics.

Unlike other methods for calculating edaphic criterion weights, the analysis revealed that the chosen approach assigned higher priority to relevance and spatial coverage, a result clearly observed in all three Peruvian cities.

Multicriteria area-based geolocation probability

The analysis of multicriteria geolocation probability using the "Fuzzy Logit" model revealed that specific areas in three cities of Peru exhibit different levels of suitability for urban development according to established criteria. The results revealed a clear distinction between high-probability zones, characterized by favourable edaphological conditions, and low-probability areas, where adverse factors, such as poor soil quality and incompatible land use, prevail. Other probabilistic models, such as the binary logistic regression model (BLRM) applied by Getu and Gangadhara Bhat (2024), introduce a data-driven approach to predicting urban growth, considering proximity to infrastructure and topographic characteristics.

Although the BLRM model was not used to determine the weights in Chanchamayo, Tarma, and Jauja cities, the "Fuzzy Logit" technique was applied to assess the probability of urban suitability. Spatial variation and area-based probabilities were evaluated using thematic variables such as soil texture, geomorphology, and economic and ecological zoning. In this regard, the findings of Rahman and Szabó (2022) were similar, as they also employed a multicriteria approach to optimize residential land allocation and estimate its suitability probability. This finding also corroborates the results of Mallick *et al.* (2022) in Abha and Khamis Mushayet, Saudi Arabia, who concluded that the integration of probabilistic models in land use planning significantly improves the accuracy of urban development predictions, emphasizing that successfully identifying suitable areas could lead to more effective urban planning and more efficient resource management.

Multicriteria geolocation based on the probability of area suitability

The geolocation analysis based on the probability of area suitability, conducted in three cities in Peru and other international studies, has utilized geospatial techniques to integrate multiple factors and generate suitability maps.

The study by Liladhar Rane *et al.* (2023) in Nashik, India, which classified areas into multiple suitability categories, demonstrated methodological parallels with the urban zone stratification applied in Chanchamayo, Tarma, and Jauja (Peru)—both relying on edaphological subcriteria for evaluation. In Nashik, 16.48% of the total area was classified as highly suitable for urban development, a finding consistent with the results of Peruvian cities, where zones were similarly tiered based on their edaphological potential (e.g., soil depth, land-use capability).

Moradi *et al.* (2023) in Tehran (Iran) emphasized the critical need for a multicriteria framework to effectively evaluate urban zones. Similarly, Al-Ghorayeb *et al.,* (2023) found that 51% of non-urbanizable land was classified as highly or very highly suitable, underscoring the influence of topographic factors and proximity to infrastructure in determining urban suitability. As part of the research, economic and ecological zoning was prioritized; however, this criterion is not applied by other authors for the geolocation of urban areas. This underscores its key importance for multicriteria geolocation in the three Peruvian cities.

In contrast, Fernandez and Schroeder (2023), in the city of Piura, employed GIS-based spatial analysis to convert illegal landfills into public spaces. However, their approach omitted edaphic criteria—specifically, economic-ecological zoning—and classified areas solely as suitable. Conversely, the comparison of the three Peruvian cities demonstrated that urban geolocation strategies can guide not only residential development but also the enhancement of public infrastructure.

Conclusion

Geomorphological characteristics—including edaphic criteria and subcriteria—were fundamental for urbanization and proved critical for designing tailored urban planning strategies in Chanchamayo, Tarma, and Jauja, thereby facilitating decisions aligned with sustainable development and ecological preservation. The Fuzzy Logit model revealed a non-linear relationship between area size and urbanization suitability, indicating that larger areas had a higher probability of experiencing urban expansion. Integrating these probabilistic assessments into the planning process provided a nuanced understanding of how edaphological factors influenced urban growth in the three Peruvian cities.The multicriteria geolocation analysis (based on urbanization probability) identified significant differences among Chanchamayo, Tarma, and Jauja. While statistical correlations between area size and urbanization probability were weak, the delineated zones offered substantial opportunities for targeted urban development.Observed variations in edaphological weightings significantly impacted urbanization potential, underscoring the need for city-specific planning strategies. This emphasized the importance of adapting approaches to each territory's unique conditions to foster sustainable urban growth.

Zones with high probability scores can yield better environmental outcomes and more efficient land-use strategies, thereby optimizing resource allocation while minimizing ecological disruption.

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Conflict of interest

The authors declare that they have no conflict of interest.

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