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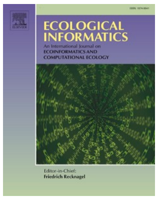

Suitability of the Amazonas region for beekeeping and its future distribution under climate change scenarios

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ABSTRACT

Beekeeping plays an important role in global food production and the conservation of wild species. However, determining territorial suitability and future distribution under climate change scenarios is a relatively understudied area in Peru. This study assessed the beekeeping suitability of the Amazonas region and its variation under climate change scenarios in two projected periods (2041–2060 and 2081–2100), according to Shared Socioeconomic Pathways (SSP). The methodological framework integrated the Analytical Hierarchy Process (AHP) with Geographic Information Systems (GIS), and the Hadley Centre Global Earth Model - Global Coupled configuration 3.1 (HadGEM3-GC31-LL) was used for future climate analysis. The beekeeping suitability of the region was determined based on eleven criteria: four climatic, three topographic, and four environmental. The results indicate that beekeeping suitability is distributed as follows: 3.4 % (1417.90 km^2) with 'High' suitability, 79.2 % (33,318.61 km^2) with 'Moderate' suitability, 17.2 % (7230.26 km^2) with 'Marginal' suitability, and 0.2 % (83.64 km^2) as 'Not suitable'. Moreover, the average temperature across the region is projected to increase by approximately 3 °C under the SSP2–4.5 scenario and between 6 °C and 8 °C under the SSP5–8.5 scenario during the projected periods. Precipitation will decrease in the northern part of the region, while the southwestern part will experience an increase. In the highly suitable beekeeping area, a temperature increases up to 10.8 °C is expected, with frequent variations around 3 °C to 8 °C, affecting more than 500 km^2. Additionally, a reduction in precipitation up to 311 mm/year is projected, with predominant variations ranging from −49.5 to −32.8 mm/year over approximately 600 km^2.Therefore, it is suggested to implement strategies to mitigate these upcoming challenges, particularly if the modeled economic development under the SSPs continues. This study modeled and mapped areas with present conditions suitable for beekeeping and future climate behavior. The modeling aims to guide beekeepers and local authorities in developing sustainable practices and implementing preventive measures to address future climatic challenges.

1. Introduction

Beekeeping is an important activity globally and has been shown to contribute to the sustainable development of rural areas, both economically by improving income and environmentally through the pollination services provided by honeybees (Fedoriak et al., 2021; Sarı et al., 2020). Furthermore, like other foods rich in polyphenols and antioxidant compounds, interest in honey has increased in recent years

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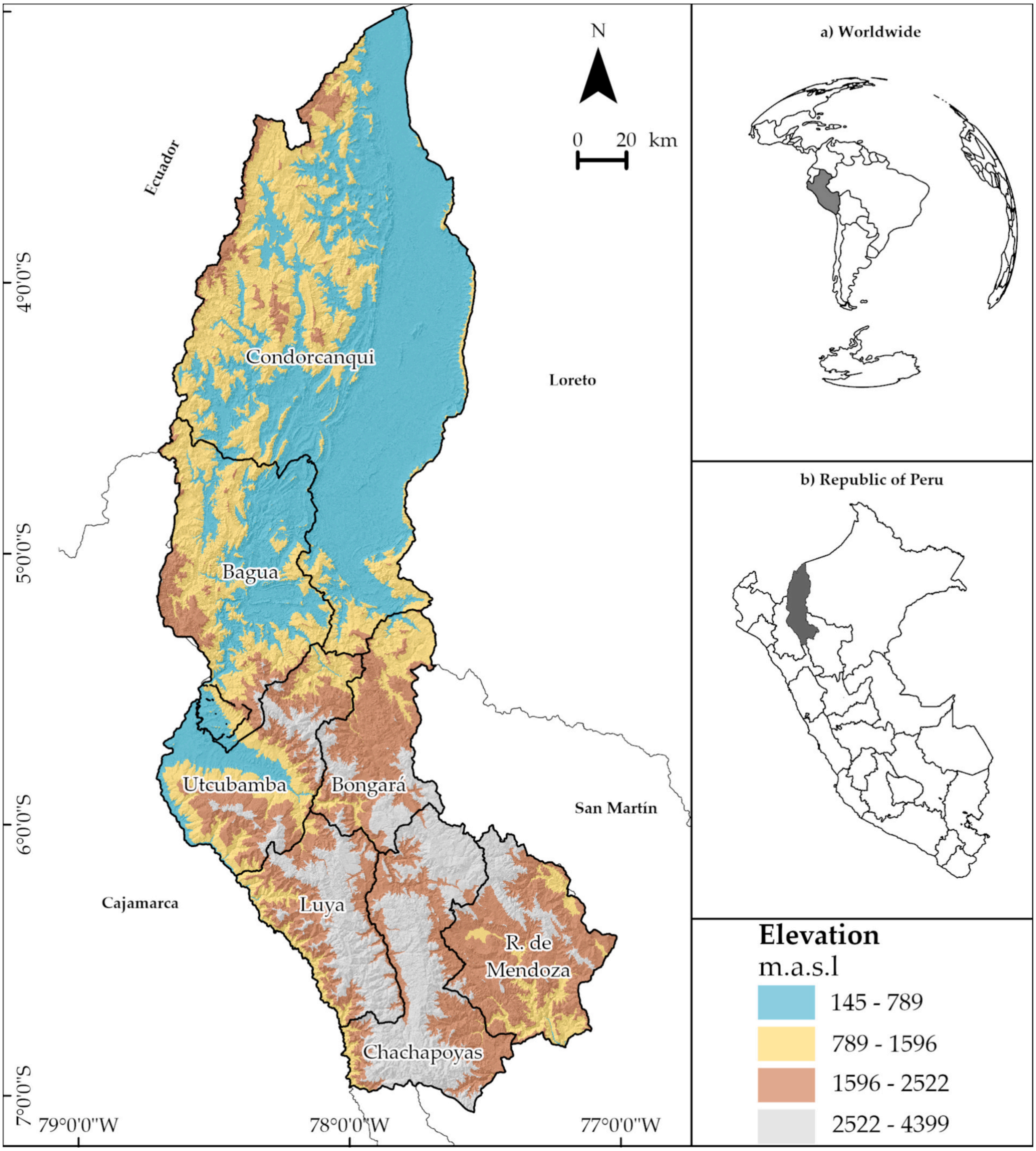


Fig. 1. Geographical location of the Amazonas region in the northwestern part of the *b)* Republic of Peru, in South America *(a)*.

due to its health benefits (Brudzynski and Sjaarda, 2021; Klein et al., 2018). Beekeeping is a nature-dependent activity; therefore, environmental changes can affect honey yield per hive. Burucu and Bal (Burucu and Gülse Bal, 2017), determined that 85 % of the differences between colonies are due to environmental conditions, with only 15 % attributed to genotype differences.

Pollinator insects, including honeybees, wild bees, and bumblebees, are essential to agriculture, contributing at least 22 billion euros annually to the European agricultural industry. However, pollinators are facing serious challenges, including a significant decline in their populations worldwide (Bommarco et al., 2012; Brittain et al., 2013). This decline has historically been linked to threatened and endangered plant species, jeopardizing fragile plant-pollinator networks (Mathiasson and Rehan, 2020). In the specific case of beekeeping, factors affecting its sustainability include population growth, consumption patterns, overexploitation of natural resources, and climate change (Defries et al., 2004; Lambin and Meyfroidt, 2011).

Although apicultural products offer numerous positive attributes, the lack of quality standards for their production and distribution can lead to the presence of contaminants, such as pesticides and mycotoxins in bee pollen (Carrera et al., 2024; Végh et al., 2021). Additionally, various studies indicate that climate change impacts beekeeping, as adverse events such as droughts, frosts, and hail negatively affect vegetation growth, and these adverse conditions promote the proliferation of pathogens that directly impact the hive (Cornman et al., 2012; Francis and Nielsen, 2013; Vercelli et al., 2021). The rise in average temperatures is altering flowering patterns and reducing the availability of nectar and pollen sources for bees (Patel et al., 2023). According to

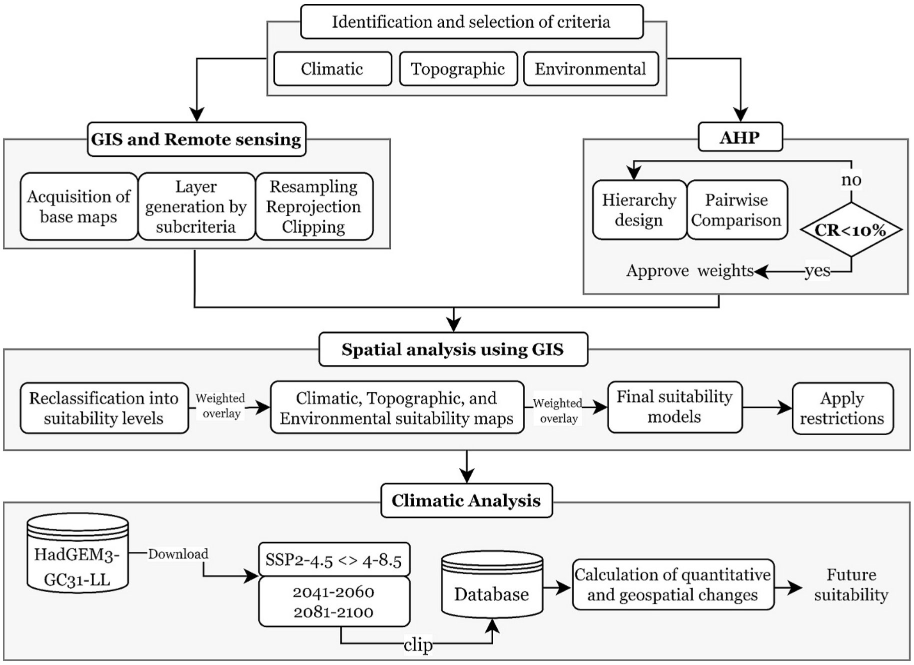


Fig. 2. Methodological diagram to model the apicultural aptitude of the Amazonas region.

recent studies in Latin America, annual honey bee colony losses average 30.4 %, with significant variations between countries and seasons, reflecting critical challenges to the health and sustainability of global beekeeping if effective climate change adaptation measures are not implemented (Buckner et al., 2024; Requier et al., 2024).

Beekeeping faces challenges such as environmental changes and bee diseases, which often arise from inadequate management and poor site selection. Among these challenges is *Varroa destructor*, a parasitic mite that can affect bee colonies. Studies have shown that management practices, such as queen replacement and nutritional supplementation, can help reduce Varroa infestation (Korená Hillayová et al., 2022; Robi et al., 2023). However, environmental changes are largely beyond the control of beekeepers, highlighting the importance of careful planning, selecting suitable locations, and implementing effective management strategies as key factors for successful beekeeping (Anderson and Trueman, 2001; Benjamin and Evans, 2012; Giacobino et al., 2014).

In the face of these challenges, identifying areas with beekeeping potential has become strategic, as it allows for efficient planning and management of resources to maintain and increase pollinator populations while simultaneously protecting the ecosystem services they provide. Tools such as Multi-Criteria Decision Analysis (MCDA), specifically the Analytical Hierarchy Process (AHP) (Saaty, 1980), can be utilized, integrated into Geographic Information Systems (GIS), and supported by data derived from Remote Sensing (RS) (Fotso Kamga et al., 2024; Mahdizadeh Gharakhanlou et al., 2025; Yahia Meddah et al., 2023). Identifying beekeeping areas is strategic because it maximizes productivity (Malczewski, 2006) while fulfilling key ecological roles by pollinating a wide range of crops (Klein et al., 2006). It also helps reduce the risk of colony losses. Therefore, suitability analyses can be valuable for managing and planning territories based on specific activities (Malczewski, 2006).

These methodologies have already been successfully applied in other regions of the world demonstrating their effectiveness in identifying areas suitable for beekeeping (Sari, 2020; Sarı et al., 2020; Sarı and Ceylan, 2017; Singh et al., 2023; Zoccali et al., 2017). In Peru, specifically in the Amazonas region, an evaluation was conducted using AHP (Cotrina-Sanchez et al., 1900). However, this study aims to incorporate a greater number of criteria and assess beekeeping suitability in the context of climate change, for example, this study evaluates additional factors such as relative humidity and susceptibility to landslides, improving previous analyses and providing more accurate information for decision-making in land management.

Therefore, the main objective was to determine the suitability of the Amazonas region for beekeeping development and its future distribution under climate change scenarios. To achieve this, two specific objectives were carried out: ***(i)*** to identify areas in the Amazonas region with optimal environmental conditions for beekeeping development, using the AHP based on expert judgment, and ***(ii)*** to evaluate the impact of climate change on the future distribution of suitable beekeeping areas in the Amazonas region by comparing the baseline period (1970–2000) with two projected periods (2041–2060 and 2081–2100) under the SSP2–4.5 and SSP5–8.5 scenarios, focusing on temperature and precipitation variables. This research aims to provide beekeepers in the Amazonas region with a practical tool to identify and prioritize areas with the most suitable conditions for beekeeping. By incorporating future climate projections, it will help beekeepers make informed decisions on site selection, potential risks and adaptation to changing environmental conditions, thereby supporting sustainable practices and ensuring the resilience of their operations in the face of climate change.

2. Materials and methods

2.1. Study area

Located in the northeastern Peruvian Andes, the Amazonas region covers approximately 42,050.40 km^2 of rugged terrain, primarily covered by the Amazon rainforest, extending along an altitudinal gradient from 120 m above sea level (m.a.s.l.) in the north to 4900 m.a.s.l. in the south (Fig. 1, 3°0′–7°2′ S, and 77°0′–78°42′ W). The region experiences contrasting climates (warm and humid, warm and dry, and temperate warm with slight humidity), with maximum temperatures reaching 40 °C in the northern lowland jungle and minimum temperatures dropping to 2 °C in the highlands of the southern boundary. Some areas experience a water deficit of 924 mm/year, while others have a surplus of up to 3000 mm/year (SENAMHI, n.d.). The Amazonas region is comprised of seven provinces: Bagua, Bongará, Chachapoyas, Condorcanqui, Luya, Rodríguez de Mendoza, and Utcubamba (INEI Perú, 2024), and is characterized by its agricultural and livestock activities,

Table 1

Source of resources for the sub-criteria considered in this analysis.

Criteria	Subcriteria	Units	Resource	Resolution native	Reference
Climatic	Annual mean temperature	°C	World Clim	30″	(Fick and Hijmans, 2017)
	Annual precipitation	mm			
	Relative humidity	%	Climatic research unit	10’	(New et al., 2002)
Topographic	Elevation	m.a.s.l	SRTM	30 m	(Farr et al., 2007).
	Terrain slope	%			
	Terrain aspect	Cardinal orientation			
	Susceptibility to landslide	Category	Geological, Mining, and Metallurgical Institute	Feature layer	(Villacorta et al., 2012).
Environmental	Floral resource	Category	Copernicus Global Land Service Land Cover	100 m	(Buchhon et al., 2020).
	Distance to the road network	km	Ministry of Transport and Communication	Feature layer	(*MTC Descarga de Datos Espaciales-Transporte Terrestre Por Carretera*, 2024)
	Distance to water bodies				
	Distance to urban centers		Ministry of Education		(MINEDU, n.d.).

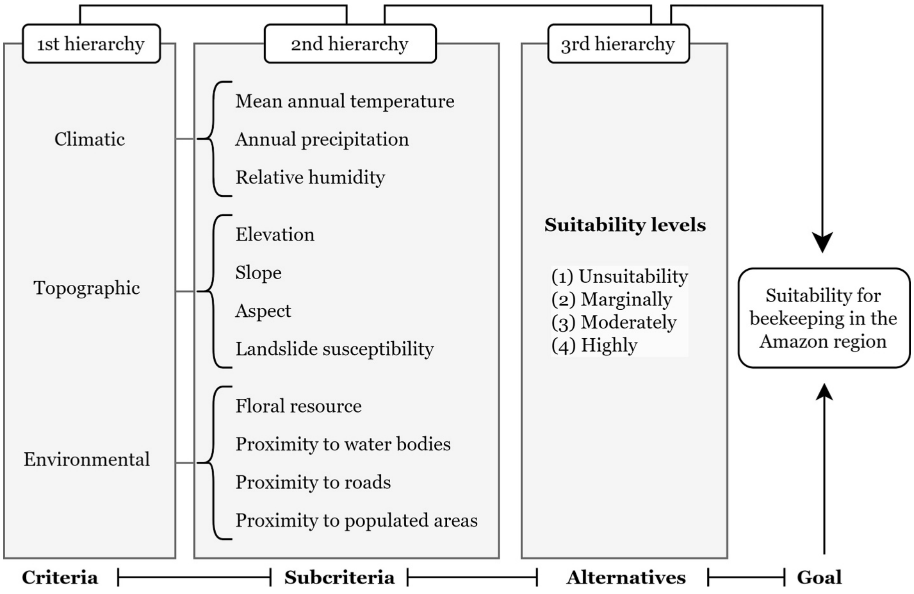


Fig. 3. Hierarchical structure considered in the modeling of beekeeping suitability in the Amazonas region.

which occupy 24.9 % of the territory and generate 51.22 % of the region’s gross domestic product (Gobierno Regional de Amazonas (GOREA), 2007).

2.2. *Methodological process*

Fig. 2 presents the methodological framework used to model current and future beekeeping under climate change scenarios in the Amazonas region. The process started with the selection of climatic, topographic and environmental criteria, followed by the acquisition and processing of geospatial data in ArcGIS Pro 3.1 (Desktop GIS Software, n.d.), including resampling, reprojection and clipping of layers. Then, the AHP was applied to prioritize the variables through expert judgment. Next, a spatial analysis was performed, combining climatic, topographic and environmental layers using a weighted overlay to generate suitability maps. Finally, future climate suitability was assessed using HadGEM3-GC31-LL temperature and precipitation data, under SSP2–4.5 and SSP5–8.5 scenarios for two periods (2041–2060 and 2081–2100), which allowed us to evaluate quantitative and geospatial changes in suitability zones.

2.3. *Mapping of the criteria that condition apiculture*

Table 1 presents geospatial information of the sub-criteria used. All sub-criteria referenced the World Geodetic System 1984 (WGS84) and were projected using the Universal Transverse Mercator projection for Zone 18 South. Finally, all data were resampled to a resolution of 30 m per pixel.

As show in Table 1, the spatial layers of precipitation and temperature were obtained from World Clim 2.1, with a spatial resolution of 30 s for the period 1970–2000 (Fick and Hijmans, 2017). Monthly relative humidity records were obtained from the Climatic Research Unit, with a spatial resolution of 10 min and a temporal average corresponding to the period 1961–1990 (New et al., 2002). Then, to generate the Relative Humidity raster layer, it was interpolated in ArcGIS Pro 3.1 using the ordinary Kriging method with a spherical semivariogram model, for its flexibility and precision in interpolation, as justified by (Rojas-Briceño et al., 2022).

The topographic variables, such as elevation, slope, and aspect, were derived from the Digital Elevation Model (DEM) generated with data from the Shuttle Radar Topography Mission (SRTM), which has a spatial resolution of 30 m (Farr et al., 2007). The susceptibility to landslide map

Table 2
Aptitude thresholds for the development of beekeeping in the Amazonas region.

Criteria/Subcriteria		Aptitude				Reference
		High	Moderate	Marginal	Unsuitable	
Climatic						
Annual mean temperature (°C)		25–37	15–25	13–15; > 37	< 13	(Abou-Shaara, 2021; Zoccali et al., 2017)
Annual precipitation (mm)		600–1000	1000–1200	300–600	< 300; > 1200	(Sari et al., 2020)
Relative humidity (%)		70–80	50–70	40–50; > 80	< 40	(Abou-Shaara, 2021)
Topographic						
Elevation (m.a.s.l)		< 1800	1800–2300	2300–3500	> 3500	(Maris et al., 2008; Tennakoon et al., 2023)
Terrain slope (%)		0–10	10–20	20–35	> 35	
Terrain aspect		Flat, Southeast, South, Southwest	East, West	Northeast, Northwest	North	(Sari et al., 2020; Sarı et al., 2020)
Susceptibility to landslide		Low and very low	medium	high	Very high	
Environmental						
Floral resource [1]		112–116	20, 40, 122–126	30, 90	0, 50–80, 100	
Distance to the road network (km)	National axis	0–1.5	1.5–5	5–10	> 10	(Campana et al., 2019; Zoccali et al., 2017)
	Departmental	0–1	1–3	3–5	> 5	
	Neighborhood	0–0.2	0.2–0.5	0.5–1.5	>1.5	
Distance to water bodies (km)	Principals	0–0.3	0.3–1.2	1.2–7	> 7	(Sarı et al., 2020; Sarı and Ceylan, 2017)
	Secondaries	0–0.1	0.1–1	1–3	> 3	
Distance to urban centers (km)	Urban areas	> 5	3–5	1–3	< 1	(Campana et al., 2019)
	Village centers	> 1.5	1–1.5	0.5–1	< 0.5	

Note: [1] Copernicus Global Land Service—Land Cover: 0–No data, 20–Shrubs, 30–Herbaceous vegetation, 40–Cropland, 50–Urban/built up, 60–Bare/sparse vegetation, 70–Snow and ice, 80–water bodies, 90–Herbaceous wetland, 100–Moss and lichen, 112–116–Closed Forest, and 122–126–Open Forest.

Table 3
Weighting scale between criteria proposed by Saaty (Saaty, 1980).

1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
Extreme ← Less important		Strong			Moderate			Equal	Moderate More important →			Strong			Extreme	

was obtained from the Geological, Mining, and Metallurgical Institute (INGEMMET) in Peru (Villacorta et al., 2012).

The Land Use and Land Cover (LULC) base map was obtained from the Copernicus Global Land Service Land Cover (CGLS—LC100)—Collection 3–2019, which has 100 m of spatial resolution (Buchhon et al., 2020). This map has limitations in identifying intervened areas, such as agricultural and urban areas. Therefore, land uses (urban and agricultural area) from the National Ecosystems Map of Peru (MINAM, 2015; MINAM, 2019), from the LULC map of the Ecological and Economic Zoning (Gobierno Regional de Amazonas (GOREA), 2007), and a map of the province of Rodriguez de Mendoza (Briceño et al., 2019) were incorporated on this map. In addition, the urban area was updated with global urban boundaries (Li et al., 2020).

The urban polygons were extracted from the final CUS map, and the population centers (points) were obtained from the Ministry of Education (MINEDU) (MINEDU, n.d.). Three road network categories (national, departmental, and neighborhood) were obtained from the Ministry of Transport and Communication (*MTC Descarga de Datos Espaciales-Transporte Terrestre Por Carretera*, 2024). Rivers from the National Charts (scale 1:100000) of the National Geographic Institute (IGN) were downloaded from MINEDU and assembled. Then, proximities to roads, rivers, and urbans were calculated using Euclidean Distance in ArcGIS 3.1.

2.4. *Identification and construction of suitability hierarchies and thresholds*

In AHP, the goal or problem is organized hierarchically into multiple levels, including a predetermined number of elements (criteria and subcriteria) (Robi et al., 2023). These criteria, which either constrain or favor beekeeping, were identified by considering previous studies on land, and technical beekeeping manuals suitability (Abou-Shaara, 2021; Campana et al., 2019; Kumar and Prasad, 2021; Sari, 2020; Sarı et al., 2020; Sarı and Ceylan, 2017; Zoccali et al., 2017). A hierarchical structure was designed, consisting of 11 subcriteria organized under the broader categories of climate, topography, and environment (Fig. 3).

To develop the third hierarchy (Fig. 3), the subcriteria were reclassified based on thresholds or suitability levels for beekeeping (Table 2) using the Framework for Land Evaluation (*Food and Agriculture Organization of the United Nations Zonificación Agro-Ecológica Guía General*, 1997). Areas with 'high suitability' are those without significant restrictions for sustainable use or with minor limitations that don't substantially affect productivity or increase associated costs. 'Moderate suitability' includes areas with moderate limitations that may reduce

Table 4
Random indexes (RI) of consistency proposed by Saaty (**Saaty, 1980**).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.525	0.882	1.115	1.252	1.341	1.404	1.452	1.484

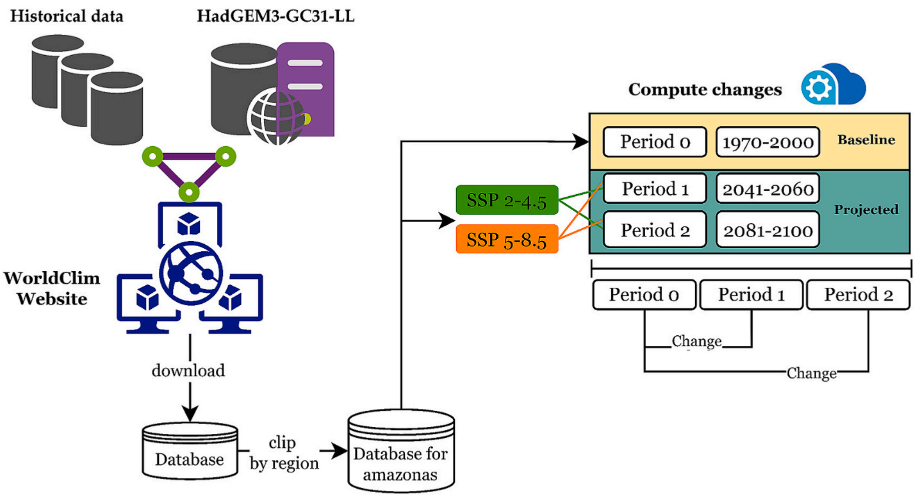


Fig. 4. Methodological scheme to analyze climate trends in the Amazonas region.

benefits or pose minor risks of soil degradation. 'Marginally suitable' areas have considerable limitations, where the cost-benefit ratio justifies their use only marginally, often for reasons beyond economic considerations. Currently 'unsuitable' areas have limitations that could be addressed through the application of technology or by assuming certain costs, though these changes are not currently viable, while permanently unsuitable areas have significant physical limitations that are considered insurmountable in the long term. As in other studies (Iliquín Trigoso et al., 2020; López et al., 2020; Madrigal-Martínez and Puga-Calderón, 2018), the currently unsuitable and permanently unsuitable areas were combined in this study.

2.5. *Criteria importance weighting by AHP method*

To obtain importance weights using AHP method, it is necessary to create Pairwise Comparison Matrices (PCM), which compare one criterion to the others in turn and establish a relative level of importance between them (Mighty, 2015). The comparison was made using the nine-point importance scale proposed by Saaty (Table 3), in which each member of a group of experts rated the criteria based on their own experience and assigned a value from least to most important (Saaty, 1980).

Table 5
Importance weights of the criteria and sub-criteria for the apiculture suitability of the Amazonas region.

Criteria	Subcriteria	Weight	Rank	Standardized weight	Rank
Climatic 46.5 %	Mean annual temperature	38.7	1	18.0	2
	Annual precipitation	29.8	2	13.9	4
	Relative humidity	31.5	3	14.7	3
Topographic 8.9 %	Elevation	19.9	2	1.8	8
	Terrain slope	17.3	3	1.5	9
	Aspect of the terrain	11.4	4	1.0	10
	Susceptibility to landslides	51.4	1	4.6	6
Environmental 44.6 %	Floral resource	53.5	1	23.9	1
	Proximity to bodies of water	8.6	3	3.8	7
	Proximity to highways	29.3	2	13.1	5
	Proximity to urban	8.5	4	3.8	7

The expert panel was composed of bee researchers and professionals from beekeeping associations and companies. The survey is permanently available on the institutional page of the Research Institute for Sustainable Development of Ceja de Selva (INDES-CES) at the following link: https://pollahp.indes-ces.edu.pe/apicultura/

The PCMs provided by the experts were processed as (Calle-Yunis et al., 2020; Hossain and Das, 2010), to obtain the importance weights corresponding to each sub-criterion and criterion. Since the subjective preferences of the experts can lead to inconsistencies in the weights obtained, the Consistency Ratio (CR) of each PCM was calculated to compare it with an acceptable inconsistency value ($CR < 0.1$) (Saaty, 1980). The CR was calculated by dividing the Consistency Index (CI) of the PCM by a Random Consistency Index (RI). This RI is defined as a function of the number of criteria (n) (Table 4), while the CI value depends on the largest or principal eigenvalue of the matrix (λ max) and n (Eq. (1)) (Saaty, 1980; Saaty, 1990).

$$CI = \frac{\lambda max - n}{n - 1} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

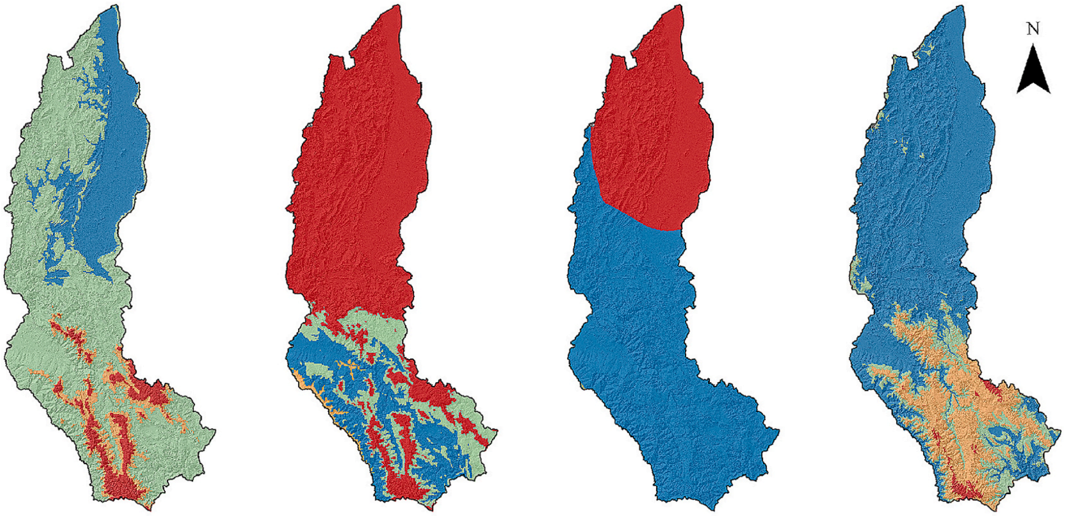
2.6. *Generation of sub-models and fitness models*

The final stage of the process of developing the second and first hierarchies consisted of integrating the reclassified thematic maps (based on Table 2) for each hierarchical group (Fig. 3) using a weighted overlay (Eq. (3)). The resulting fitness (GRIDresult) depended on the score assigned to the reclassified map pixel ($GRID_i$) and the importance weight assigned to the subcriterion ($WEIGHT_i$), which was calculated using the PCMs. The integration of the sub-criteria resulted in the creation of climatic, topographic, and environmental suitability sub-models, and the integration of these sub-models resulted in the final suitability model.

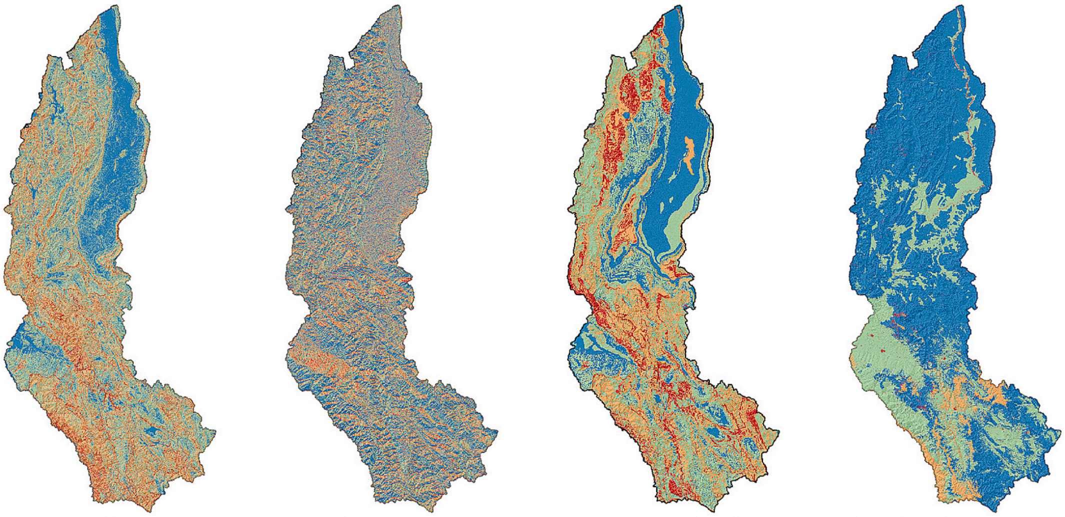
$$GRIDresult = \sum[(GRID_i)(WEIGHT_i)] \tag{3}$$

2.7. *Assessment of climate trends along shared socioeconomic pathways*

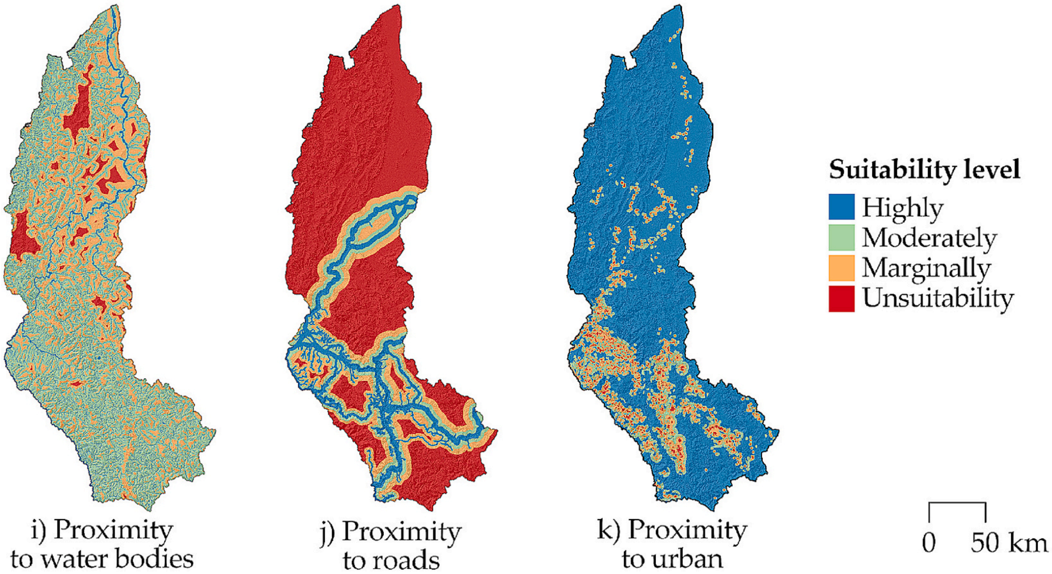
The analysis was conducted both regionally and in more detail in the currently most suitable beekeeping areas. Climate trends were analyzed according to the Coupled Model Intercomparison Project 6 (CMIP6) scenario set of the World Climate Research Program (WCRP). This set of scenarios is a function of emissions driven by different common Socio-economic pathways, and are called Shared Socioeconomic Pathways



a) Temperature b) Precipitation c) Humidity relative d) Elevation



e) Slope f) Aspect g) Landslide susceptibility h) Floral resource



i) Proximity to water bodies j) Proximity to roads k) Proximity to urban

Fig. 5. Suitability of climatic (a-c), topographic (d-g), and environmental (h-k) sub-criteria for beekeeping in Amazonas.

Table 6
Areas of sub-criteria according to aptitude for the development of beekeeping in the Amazonas region.

Criteria/Subcriteria	Aptitude							
	High		Moderate		Marginal		Not suitable	
	km^2	%	km^2	%	km^2	%	km^2	%
Climatic								
Mean annual temperature	9667.14	23.0	26,521.00	63.1	3066.04	7.3	2796.21	6.6
Annual precipitation	7030.00	16.7	6580.63	15.6	516.90	1.2	27,922.86	66.4
Relative humidity	27,379.47	65.1	10.10	0.0	14,581.33	34.7	79.50	0.2
Topographic								
Elevation	28,586.36	68.0	5322.65	12.7	7484.38	17.8	657.01	1.6
Terrain slope	11,329.15	26.9	14,251.73	33.9	13,151.26	31.3	3318.25	7.9
Aspect of the terrain								
Susceptibility to landslides	9824.74	23.4	13,936.75	33.1	13,383.16	31.8	4905.74	11.7
Environmental								
Floral resource	27,837.19	66.2	11,528.83	27.4	2251.38	5.4	433.00	1.0
Proximity to bodies of water	4491.96	10.7	22,606.63	53.8	12,516.50	29.8	2435.31	5.8
Proximity to highways	4920.76	11.7	4589.45	10.9	5395.05	12.8	27,145.13	64.6
Proximity to urban	32,891.38	78.2	4385.41	10.4	3862.78	9.2	910.83	2.2

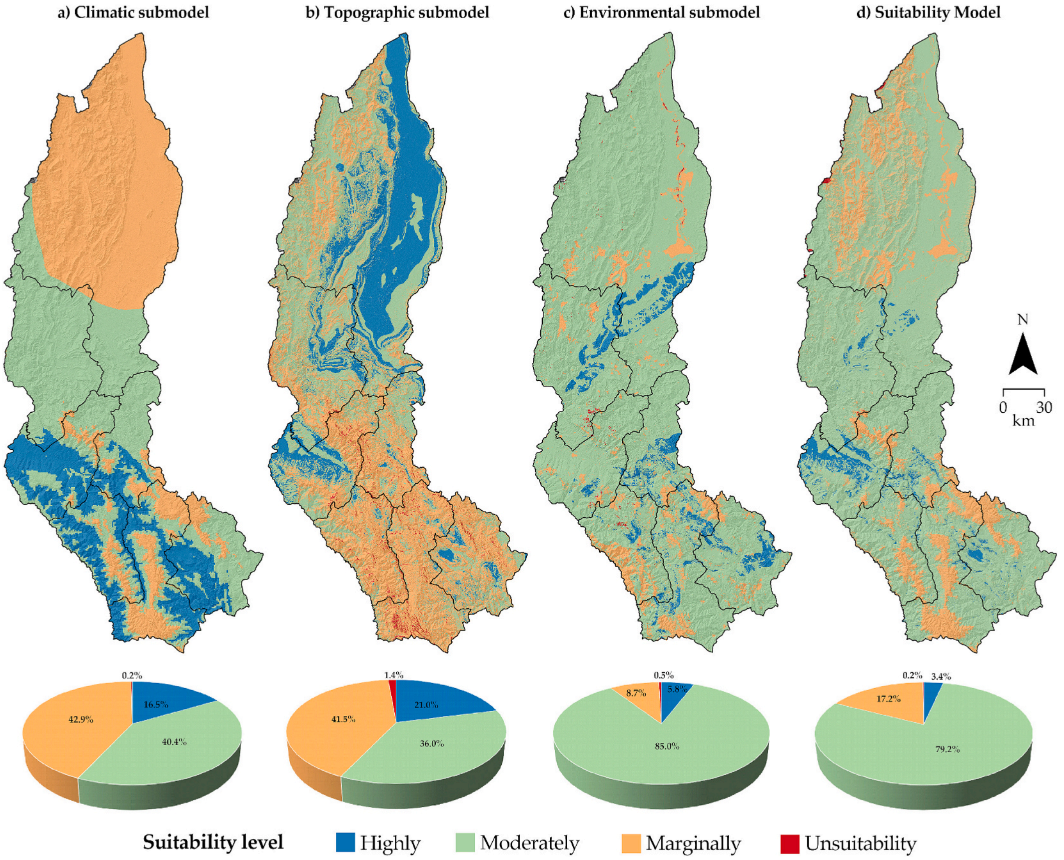


Fig. 6. Suitability model a) climatic, b) topographic, c) environmental, and d) beekeeping suitability with their respective proportional areas.

(SSPs) (O'Neill et al., 2016).

The new scenarios used represent different levels of socio-economic development and greenhouse gas emissions in the atmosphere (O'Neill et al., 2016). In contrast to the set of scenarios presented in CMIP 5, which focused on four Representative Concentration Pathway (RCP) (the RCP 2.6, 4.5, 6.0, and 8.5), the new scenarios are called SSP1–2.6, SSP2–4.5, SSP4–6.0, and SSP5–8.5, additionally, models SSP1–1.9, SSP4–3.4, SSP5–3.4OS and SSP3–7.0 were presented (O'Neill et al., 2016).

In this study, we analyzed the SSP2–4.5 scenario called "The middle of the road or middle path", in which there is low cooperation between states and population growth is moderate, stabilizing in the second half of the century. The SSP5–8.5 scenario was also evaluated, in which development is based on the overexploitation of fossil fuels, and the world economy and environmental problems are growing (O'Neill et al., 2016).

The above scenarios were analyzed for two projected periods, Projected period 1: 2041–2060 and Projected period 2: 2081–2100, using the Hadley Centre Global Earth Model - Global Coupled configuration 3.1 (HadGEM3-GC31-LL), recognized as one of the most climate-

Table 7
Area of each submodel and model of aptitude for beekeeping, by province of Amazonas.

Province	Suitability level							
	High		Moderate		Marginal		Not suitable	
	km^2	%	km^2	%	km^2	%	km^2	%
Climatic								
Bagua	112.15	1.9	5628.71	96.0	115.76	2.0	4.54	0.1
Bongará	635.37	21.0	1985.53	65.7	400.09	13.2	0.00	0.0
Chachapoyas	1466.56	32.5	1296.97	28.8	1743.47	38.7	0.00	0.0
Condorcanqui	0.00	0.0	3283.28	18.4	14,515.27	81.2	75.28	0.4
Luya	1485.45	47.9	1091.67	35.2	523.23	16.9	0.00	0.0
Rodríguez de Mendoza	1264.81	34.1	1985.77	53.5	463.58	12.5	0.08	0.0
Utcubamba	1967.79	49.5	1722.04	43.3	283.00	7.1	0.00	0.0
Total	**6932.13**	**16.5**	**16,993.96**	**40.4**	**18,044.41**	**42.9**	**79.90**	**0.2**
Topographic								
Bagua	714.10	12.2	3075.72	52.5	2042.85	34.9	28.49	0.5
Bongará	146.85	4.9	990.82	32.8	1826.39	60.5	56.93	1.9
Chachapoyas	72.16	1.6	655.89	14.6	3553.12	78.8	225.84	5.0
Condorcanqui	6808.56	38.1	7373.95	41.3	3614.70	20.2	76.62	0.4
Luya	55.27	1.8	549.69	17.7	2394.01	77.2	101.38	3.3
Rodríguez de Mendoza	245.15	6.6	1108.32	29.8	2315.65	62.3	45.11	1.2
Utcubamba	797.45	20.1	1397.63	35.2	1718.49	43.3	59.26	1.5
Total	**8839.55**	**21.0**	**15,152.02**	**36.0**	**17,465.21**	**41.5**	**593.62**	**1.4**
Environmental								
Bagua	500.68	8.5	5033.10	85.9	288.22	4.9	39.17	0.7
Bongará	375.73	12.4	2468.50	81.7	176.23	5.8	0.53	0.0
Chachapoyas	363.74	8.1	3270.87	72.6	869.45	19.3	2.93	0.1
Condorcanqui	609.48	3.4	16,139.97	90.3	990.93	5.5	133.44	0.7
Luya	162.17	5.2	2104.05	67.9	804.40	25.9	29.74	1.0
Rodríguez de Mendoza	354.11	9.5	3064.89	82.5	293.42	7.9	1.81	0.0
Utcubamba	85.88	2.2	3644.18	91.7	225.47	5.7	17.29	0.4
Total	**2451.78**	**5.8**	**35,725.56**	**85.0**	**3648.13**	**8.7**	**224.92**	**0.5**
Beekeeping Suitability								
Bagua	160.56	2.7	5526.39	94.3	166.82	2.8	7.38	0.1
Bongará	185.30	6.1	2463.29	81.5	372.40	12.3	0.00	0.0
Chachapoyas	87.90	2.0	2861.20	63.5	1557.86	34.6	0.06	0.0
Condorcanqui	74.63	0.4	14,024.99	78.5	3698.91	20.7	75.30	0.4
Luya	50.09	1.6	2432.38	78.5	617.83	19.9	0.06	0.0
Rodríguez de Mendoza	168.02	4.5	3077.45	82.9	468.68	12.6	0.09	0.0
Utcubamba	691.40	17.4	2932.92	73.8	347.76	8.8	0.75	0.0
Total	**1417.90**	**3.4**	**33,318.61**	**79.2**	**7230.26**	**17.2**	**83.64**	**0.2**

sensitive CMIP6 models (Williams et al., 2018), and available in the future data on the World Clim website. Changes were calculated for mean annual temperature and precipitation, in °C and mm, respectively. These changes were based on the historical/baseline data available at World Clim for 1970–2000 (Fig. 4).

3. Results

3.1. Criteria importance weights

Twenty-eight PCMs were constructed, three at the sub-criterion level and one at the criterion level for each of the seven experts who completed the surveys. The former experts work in public agricultural institutions and belong to beekeeping associations or companies. The information presented in Table 5 indicates the weighted relevance values assigned to each sub-criterion and criterion. The climatic (46.5 %) and environmental (44.6 %) criteria are the most important, followed by topographical (8.9 %). The sub-criteria, mean annual temperature (38.7 %), susceptibility to landslides (51.4 %), and floral resource (53.5 %) obtained the highest weighting for their group of criteria; while those with the lowest weighting were annual precipitation (29.8 %), terrain aspect (11.4 %) and proximity to populations (8.5 %).

3.2. Suitability at the sub-criteria level

Fig. 5 presents the reclassification of the climatic, topographic, and environmental sub-criteria, considering the suitability thresholds (Table 2). Complementarily, Table 6 provides the areas corresponding to each suitability threshold of the sub-criteria.

The sub-criteria with the largest area of "High" suitability concerning their group of criteria are relative humidity (27,379.47 km^2, 65.1 % of the region), elevation (28,586.36 km^2, 68.0 %) proximity to urban (32,891.38 km^2, 78.2 %). While those with the largest 'Unsuitable' area are annual precipitation (27,922.86 km^2, 66.4 %), aspect (9824.74 km^2, 23.4 %), and proximity to highways (27,145.13 km^2, 64.6 %).

3.3. Model and sub-models of aptitude of the Amazonas territory for beekeeping

The Climatic, Topographic, and Environmental submodels were obtained through the weighted superposition of the corresponding subcriteria. The 3 submodels generated the model of suitability to develop beekeeping in the Amazonas region. The submodel with the largest area of high suitability for beekeeping is the topographic (8839.55 km^2, 21.0 % of the region) followed by the climatic (6932.13 km^2, 16.5 %), and environmental (2451.78 km^2, 5.8 %).

Regarding the final suitability model, 3.4 % (1417.90 km^2), 79.2 %

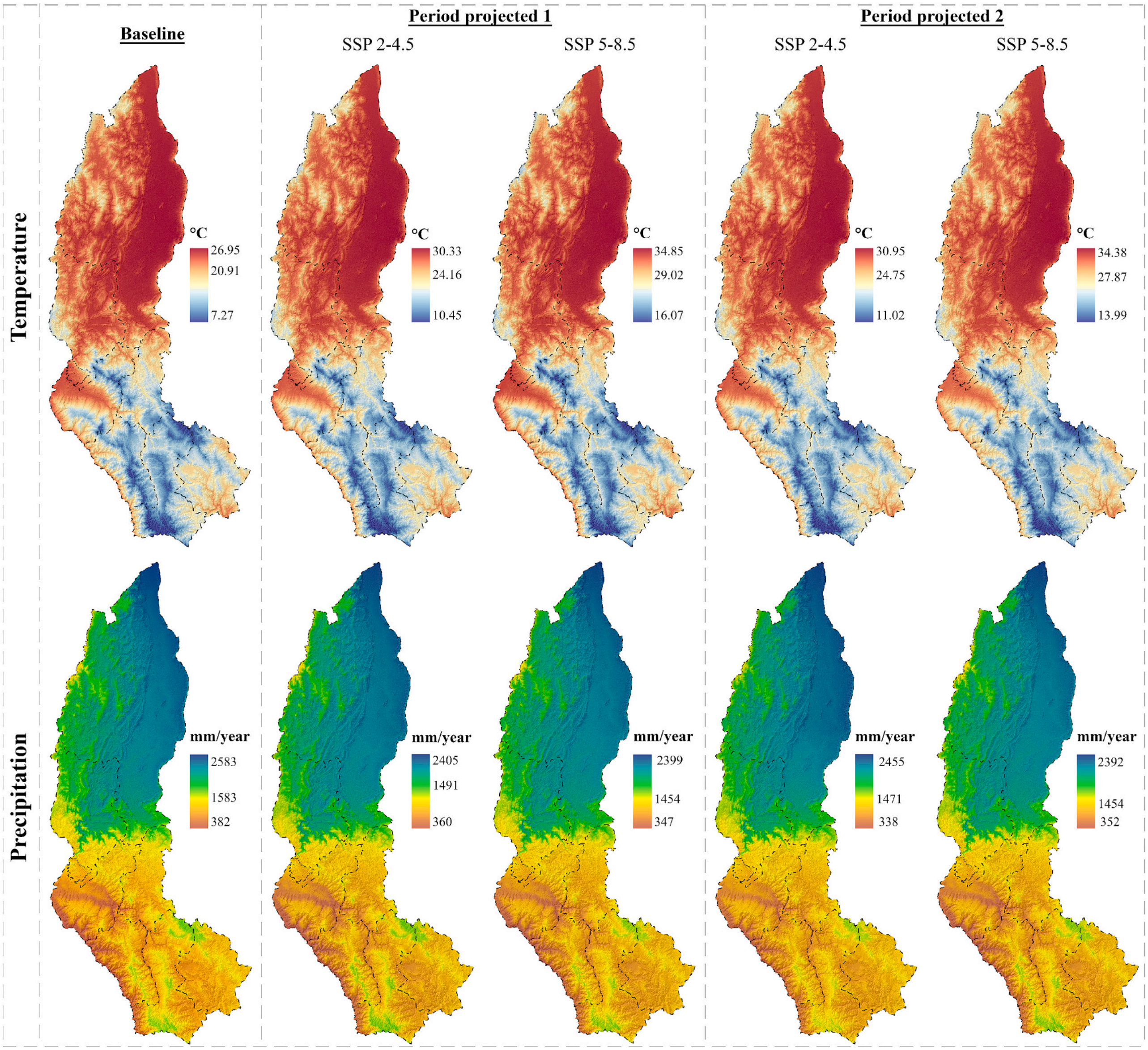


Fig. 7. Spatial distribution of average annual temperature and precipitation in the Amazonas region under climate change scenarios.

(33,318.61 km^2), 17.2 % (7230.26 km^2), and 0.2 % (83.64 km^2) of the Amazonas territory presented 'High', 'Moderate', 'Marginal' and 'Unsuitable' suitability, respectively, for beekeeping (See Fig. 6).

In addition, Table 7 provides the corresponding areas of each province according to the suitability for each submodel and the beekeeping suitability model.

At the provincial level, Utcubamba (1967.79 km^2), Luya (1485.45 km^2), Chachapoyas (1466.56 km^2), and Rodríguez de Mendoza (1264.81 km^2) stand out with the largest area of 'High' suitability in the climatic submodel. In the topographic submodel, Condorcanqui (6808.56 km^2), Utcubamba (797.45 km^2), and Bagua (714.10 km^2) stand out. And, in the topographic submodel, all provinces have a similar area of high suitability. Likewise, Utcubamba (691.40 km^2), Bongará (185.30 km^2), Rodríguez de Mendoza (168.02 km^2), and Bagua (160.56 km^2) have the largest areas with 'High' suitability in the final beekeeping suitability model, while Chachapoyas (87.90 km^2), Condorcanqui (74.63 km^2) y Luya (50.09 km^2) have the smallest areas of 'High' suitability in the topographic submodel.

3.4. Climate trends according to shared socioeconomic pathways (SSP)

3.4.1. Baseline and projected spatial distribution of temperature and precipitation

Fig. 7 shows the spatial distribution of average annual temperature and precipitation in the Amazonas region, comparing the base period with projected periods 1 and 2 under SSP 2–4.5 and 5–8.5.

During the first projection period (2041–2060) under the SSP2–4.5 scenario, an increase in temperature is observed with average values of 24.16 °C, reaching minimum values of 10.45 °C and maximum values of 30.33 °C. Under the SSP5–8.5 scenario, the average is slightly higher, with 29.02 °C, and a range of 16.07 °C to 34.85 °C. For the second projection period (2081–2100), both scenarios indicate an increase in temperature, especially in the northern sector of the region. SSP2–4.5 shows a range of 11.02 °C to 30.95 °C with an average of 24.75 °C, while SSP5–8.5 exhibits a more pronounced increase with temperatures ranging from 13.99 °C to 34.38 °C and an average of 27.87 °C.

For the average annual precipitation, during the first period projected under SSP2–4.5, there is a decrease in average precipitation to 1491 mm/year, from a minimum of 360 mm/year to a maximum of 2405 mm/year concerning the base period. Under the SSP5–8.5

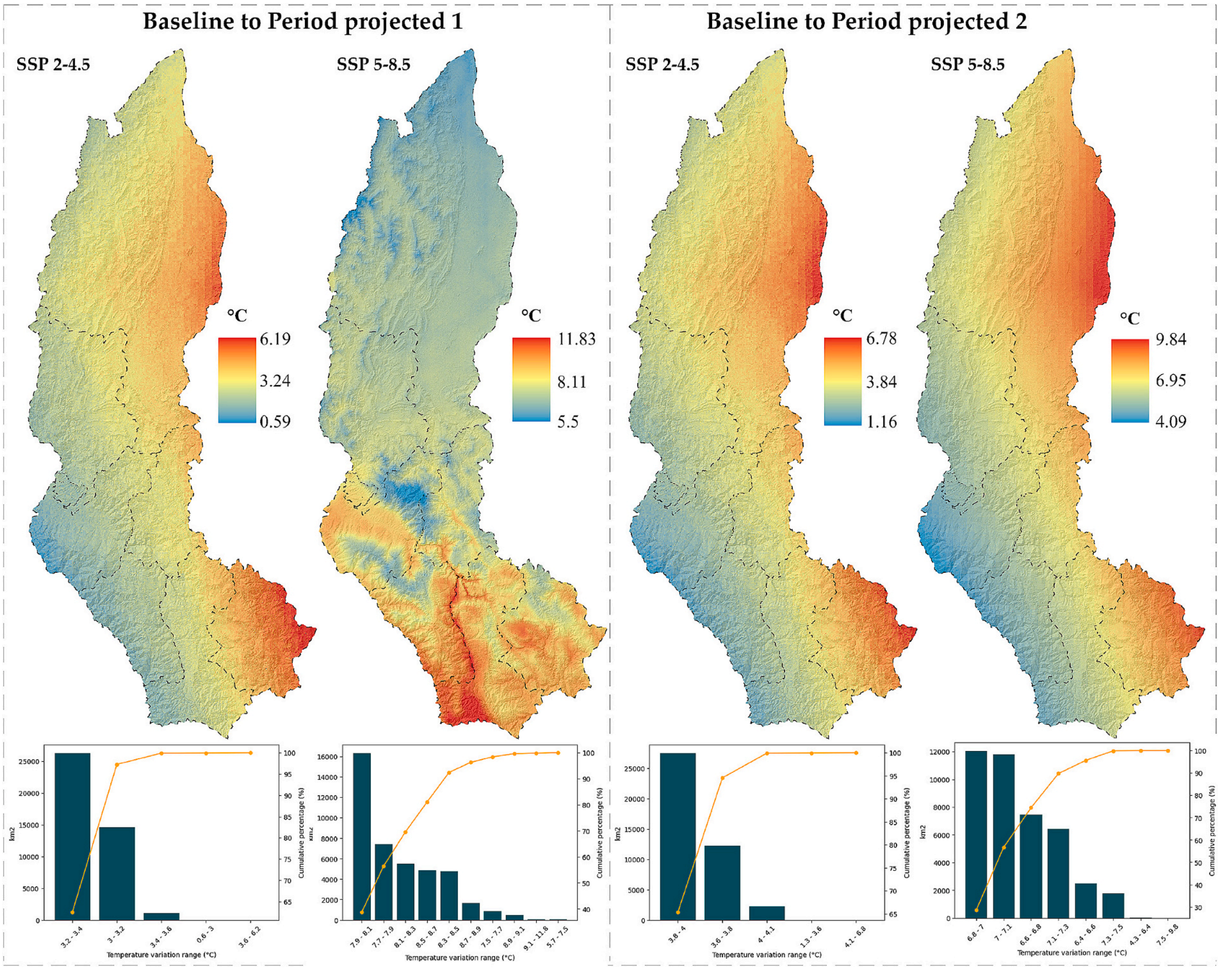


Fig. 8. Geospatial and quantitative changes in mean annual temperature in Amazonas under climate change scenarios.

scenario, a similar decrease is observed with an average of 1454 mm/year, varying from 347 to 2399 mm/year. In the second projection period, the SSP2–4.5 scenario also shows a decrease in the average of 1471 mm/year and a range of 338 to 2455 mm/year, while under SSP5–8.5, precipitation averages 1454 mm/year, fluctuating between 352 and 2392 mm/year.

3.4.2. Changes in records at the regional level

The geospatial and quantitative changes in temperature and precipitation between the base period and the projected periods according to the SSP 2–4.5 and SSP 5–8.5 scenarios are shown in Figs. 8 and 9. According to the projections and scenarios considered, increases in average annual temperature are expected especially in the northern and southeastern areas of the Amazonas region.

Although the temperature and precipitation change projections show marked variations in certain areas, it is necessary to consider the geographic extension that will experience these changes to evaluate their real impact. Therefore, the subfigures show the areas covered by the most frequent variations, represented in Deep cyan bars by variation intervals and the cumulative percentage of these variations (orange line).

During the first projection period, the SSP 2–4.5 presents an average increase of 3.24 °C, with a range of 0.59 °C to 6.19 °C, a scenario in which the greatest variation (65 %) will be between 3.2 and 3.4 °C, covering more than 25,000.00 km^2. On the other hand, SSP 5–8.5 scenario shows an average temperature increase of 8.11 °C for the base period, with variations ranging from 5.5 °C to 11.83 °C. In this scenario, more than 16,000.00 km^2 will present variations of 7.9 to 8.1 °C, representing approximately 35 % of the estimated variations.

For the second projection period, the SSP 2–4.5 scenario shows an average increase of 3.84 °C, with changes from 1.16 °C to 6.78 °C, a scenario in which the greatest variation (67 %) will be between 3.8 and 4 °C, covering more than 25,000.00 km^2. On the other hand, the SSP 5–8.5 indicates a more marked increase with an average of 6.95 °C and variations from 4.09 °C to 9.84 °C, where 60 % of the variations are between 6.8 and 7 °C and 7.7–1 °C, covering almost 24,000.00 km^2 of the Amazonas region.

Likewise, in the Amazonas region, changes in precipitation according to the SSP 2–4.5 and SSP 5–8.5 scenarios during the projected periods show variations in both increases and decreases. Next, Fig. 9 shows how precipitation in the Amazonas region will increase and decrease in all scenarios and periods projected.

Specifically, from the Base Period to Projected Period 1 and following SSP 2–4.5, precipitation in the northeast is expected to decrease to 650 mm/year, while in the southwest it is expected to increase to 394 mm/year, with a regional average decrease of 92 mm/year.

Thus, about 14,000.00 km^2 will show decreases ranging from 62.8 to 95.4 mm, representing approximately 30 % of the estimated variations. On the other hand, according to SSP 5–8.5, the northern sector will continue to decrease to 696 mm/year, and the southwestern sector will see an increase of up to 351 mm/year, with a regional average decrease of 130 mm/year. Thus, the most frequent decreases in precipitation will be from 139.8 to 172.5 (63 %), affecting more than 26,000.00 km^2.

For projected period 2, the SSP 2–4.5 scenario, in the Northeast sector, precipitation will decrease by 690 mm/year, as opposed to the

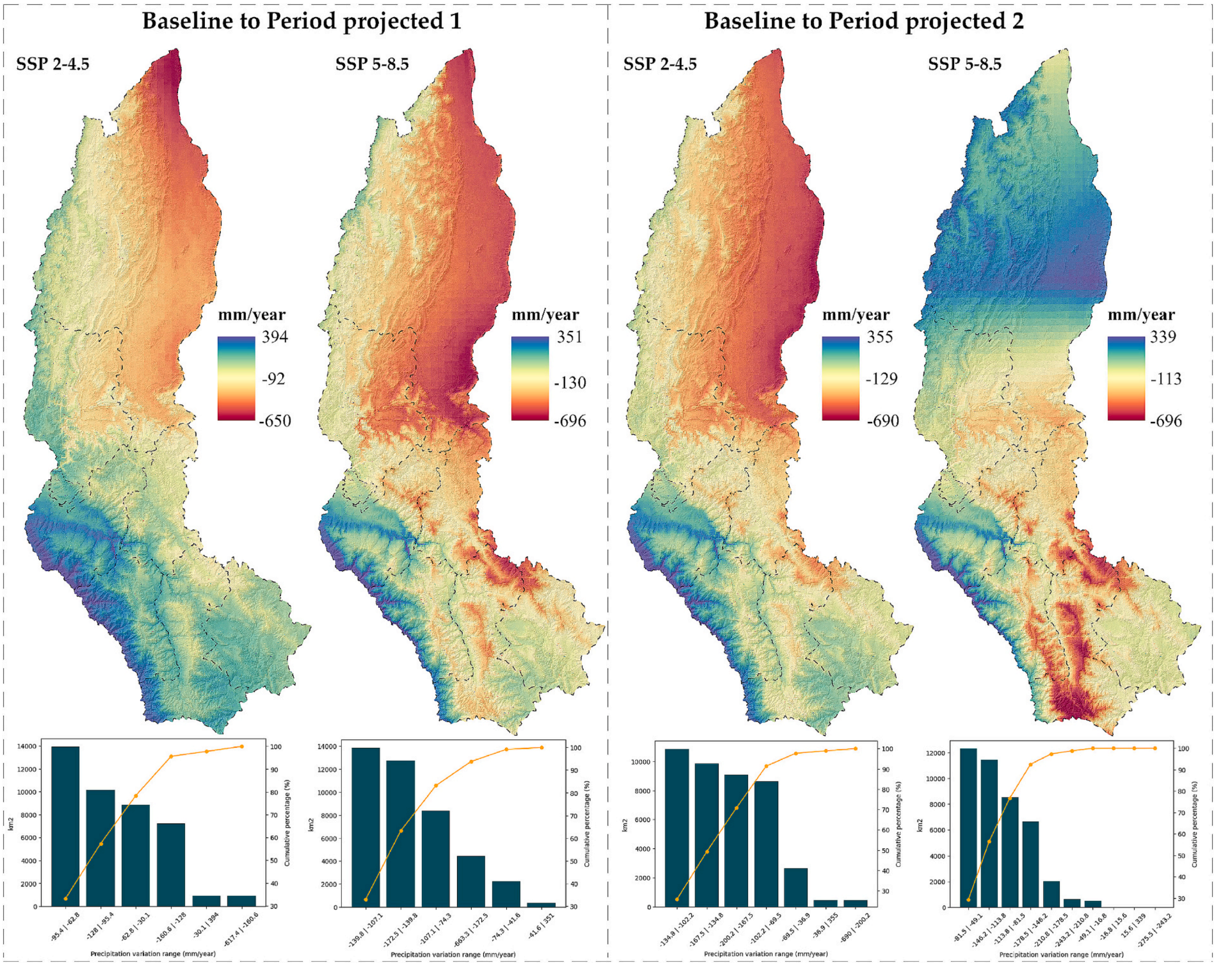


Fig. 9. Geospatial and quantitative changes of mean annual precipitation in Amazonas under climate change scenarios.

Southwest sector, which will register increases of 355 mm, with an average regional decrease of 129 mm/year. Thus, the largest decrease in precipitation (29 %) will range from 102.2 to 134.8, covering more than 10,500.00 km^2. Finally, according to SSP 5–8.5, the North sector will continue to decrease up to 696 mm/year, and the Southwest sector will see an increase of up to 339 mm/year, with an average regional decrease of 113 mm/year. Thus, the greatest variations (29 %) will be between 49.1 and 81.5 mm/year, hosting more than 12,000.00 km^2 of the Amazonas region.

3.4.3. Changes to records in the high-suitability area

Figs. 10 and 11 show the geospatial and quantitative changes in average annual temperature (C°) and precipitation (mm) of the 1417.90 km^2 categorized as high suitability for beekeeping. Also, the subfigures show the areas covered by the most frequent variations, represented in Deep cyan bars by variation intervals and the accumulative percentage of these variations (orange line).

Fig. 10 shows that, from the Base Period to Projected Period 1 and following SSP 2–4.5, temperature average annual increase of 3.19 °C, with ranges from 1.2 °C to 5.6 °C, in this scenario the greatest variation (60 %) will be from 3.1 to 3.3 °C, hosting about 1000.00 km^2 of highly suitable area for beekeeping. The opposite case, according to SSP 5–8.5, the average temperature will increase by 8.38 °C, with ranges from 6.3 °C to 10.8 °C, but most of the variations (32 %) will be between 8.4 and 8.5 °C and will occur in about 500 km^2.

For Projected Period 2, following SSP 2–4.5, the average temperature is expected to increase by 3.78 °C, with variations from 1.8 to 6.1 °C, but the most frequent variation (57 %) will be 3.7–3.9 °C, affecting more than 800 km^2. On the other hand, for SSP 5–8.5, it is estimated that the average temperature will increase by 6.77 °C, with variations from 4.8 to 9.2 °C, in which 30 % of the variations will be between 6.6 and 6.7, affecting more than 400 km^2 of the area suitable for beekeeping in Amazonas.

Likewise, in the area highly suitable for beekeeping, the changes in precipitation according to the SSP 2–4.5 and SSP 5–8.5 scenarios during the projected periods show variations in both increases and decreases (Fig. 11).

From the base period to projected period 1, under the SSP 2–4.5 scenario, precipitation decreases will be recorded in the currently suitable area in the northern sector, which includes the provinces of Bagua and Condorcanqui. On the other hand, precipitation increases will be recorded in the currently suitable areas of the South and Southwest sectors (Utcubamba, Luya, and Rodriguez de Mendoza provinces).

On average, precipitation will decrease by 59 mm/year with variations between −266 to 311 mm. In this scenario, about 600 km2 will show decreases between 32.8 and 49.5 mm, which represents about 40 % of the estimated variations. In SSP 5–8.5, average precipitation decreases of 94 mm/year are expected, with variations from −311 to 230 mm/year; in this case, the most frequent precipitation decreases (25 %) will be from 57.4 to 74.3, affecting more than 350 km^2.

In the transition to projection period 2, under the SSP 2–4.5 scenario, precipitation will decrease by an average of 86 mm/year. In the northern sector, precipitation will decrease by up to 306 mm, while in the southwestern sector, increases of up to 237 mm/year will be recorded, of which a total of approximately 400 km^2 will experience decreases of 51.5 to 68.4 mm, representing 30 % of the estimated variations.

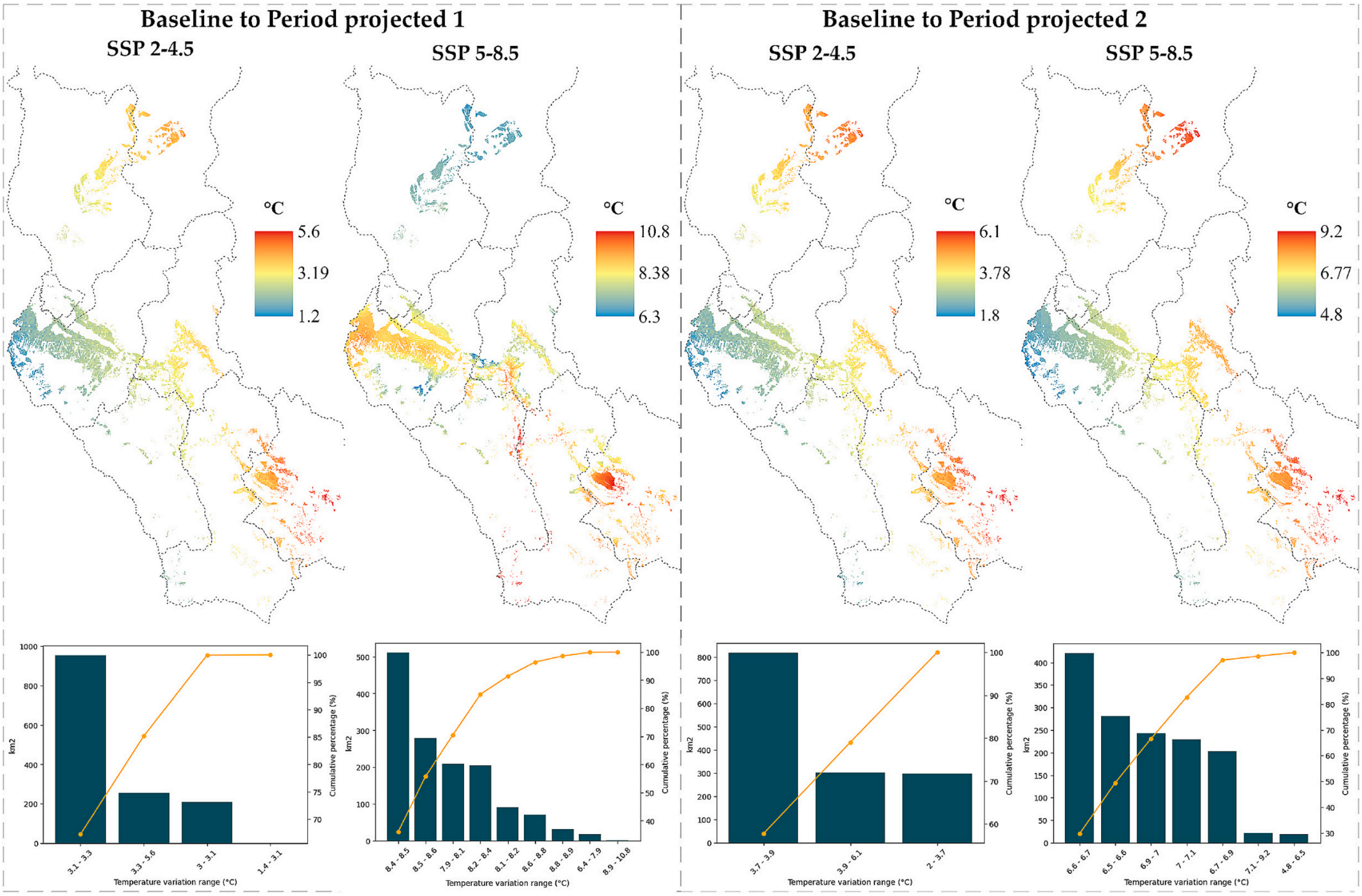


Fig. 10. Geospatial and quantitative variation of mean annual temperature (°C) in the area suitable for beekeeping in Amazonas region.

On the other hand, according to SSP 5–8.5, the northern sector and the provinces of the southern sector (Bongará, Luya, Chachapoyas and R. de Mendoza) will register precipitation decreases of up to 310 mm/year and increases of 206 mm/year, but the largest area (350 km2 approx.) will register decreases of 116.5 to 132.6 mm/year, representing more than 20 % of estimated variations in the area suitable for beekeeping in Amazonas.

4. Discussion

The sub-criteria used in suitability analyses directly influence the suitability models and sub-models (López et al., 2020). In this research, we integrated 11 sub-criteria to determine the suitability of land for the current and future development of beekeeping in the Amazonas region. For suitability analyses in general, various MCDA techniques are used (Calle Yunis et al., 2020; Cotrina-Sanchez et al., 1900; Fotso Kamga et al., 2024; Hossain and Das, 2010; Kumar and Prasad, 2021; Maris et al., 2008; Sari, 2020; Zoccali et al., 2017). In our case we used the AHP, unlike Sari and Ceylan (Sarı et al., 2020), who obtained suitability models under 3 MCDA techniques, the AHP, the Serbian method VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), reporting similarities between AHP and VIKOR, leaving to research criteria the validation approach to select the MCDA technique.

Unlike Sari and Ceylan (Sarı and Ceylan, 2017), who used 8 sub-criteria, in our case we included in the analysis: average annual temperature and humidity as climatic sub-criteria, and susceptibility to landslides as environmental sub-criteria. Therefore, in this study, we evaluated the territory using 11 suitability sub-criteria. The climatic conditions, topographic diversity, and environmental criteria enriched the results and the reliability of the suitability model for apiculture in the Amazonas region.

We agree with Sari and Ceylan (Sarı and Ceylan, 2017), who determined that the floral resource is the most important sub-criterion for the development of beekeeping, reporting 44 %; we reported 23.9 % of importance (Table 6). It should be added that the lack of availability of a temporal flora map and information on plant density, which are important for bees, is particularly limited to the AHP - GIS model generated. Therefore, we used free high-resolution images (Planet, Sentinel 2 A/B) to be able to obtain an accurate, robust, and realistic classification.

For different topographic, physical, and climatic conditions, as in the study area, beekeeping activities are enhanced due to the probability of increased honey season, therefore, beekeepers can increase honey production following different seasons (Pujiastuti et al., 2024). At this point, this study reveals two main issues for beekeepers to increase their honey production according to the availability of floral resources.

The results establish for beekeepers both a route to migrate and the start and end dates of migration. In addition, the concept of beekeeping suitability reveals suitable areas that beekeepers had never located before, and by establishing new apiaries, new beekeeping areas are specified, and honey production is increased (Singh et al., 2023).

On the other hand, Langowska et al. (Langowska et al., 2017), evaluated the effect of temperature anomalies on honey production for the period 1965–2010, reporting later final harvests and longer seasons in periods of high temperatures, thus identifying a negative impact on the planning of activities. Therefore, as a preventive measure and early information, we report the main changes in temperature and precipitation in the Amazonas region, as well as a detailed analysis of the currently high zone for beekeeping, for the periods 2041–2060 and

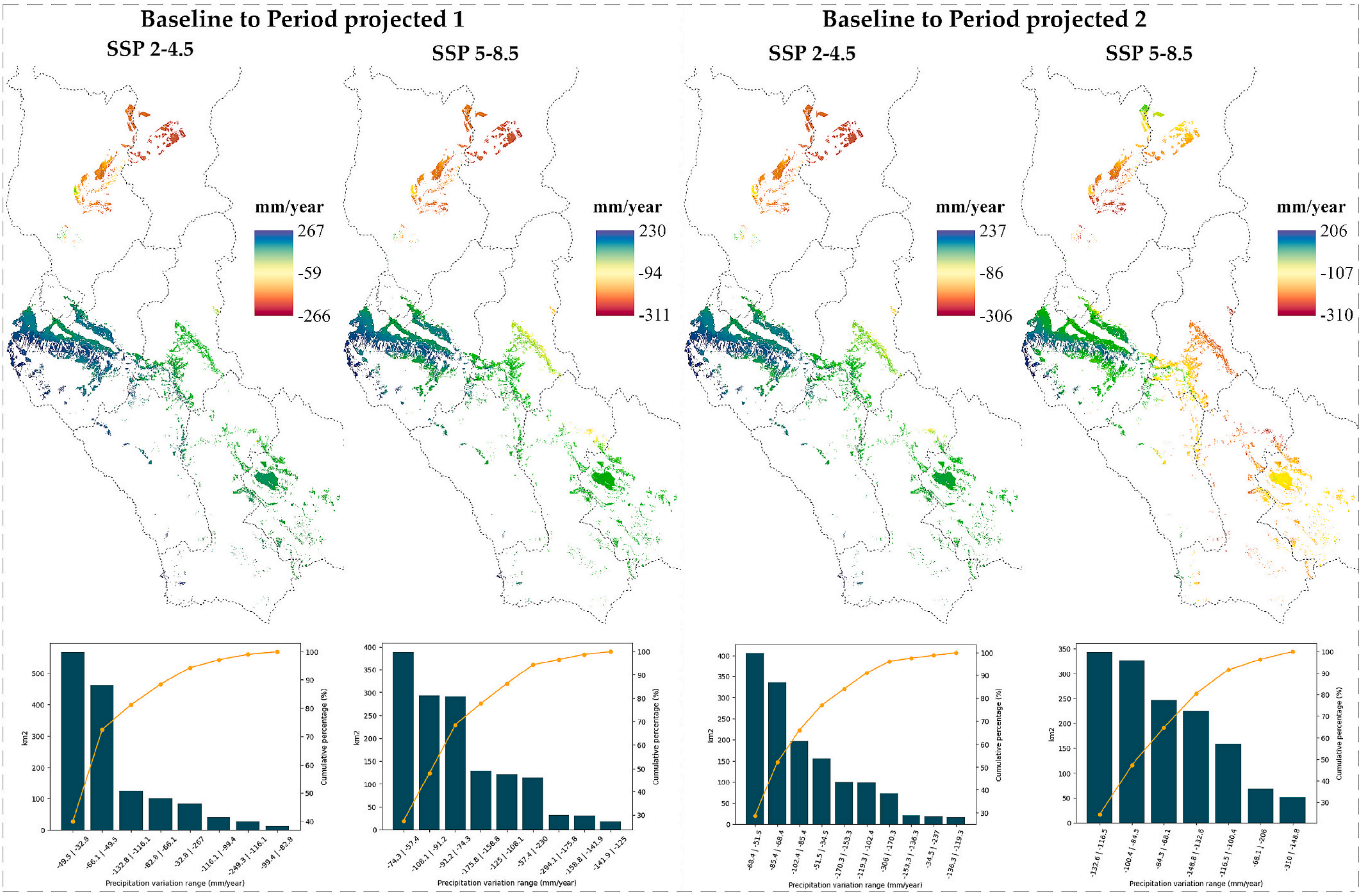


Fig. 11. Geospatial and quantitative variation of mean annual precipitation (mm) in the area suitable for beekeeping in Amazonas region.

2081–2100, according to HadGEM3 modeled data.

Temperatures are projected to increase throughout the region, with more marked increases in the northeastern sector and less in the southwestern part of the region, while precipitation will decrease sharply in the northern sector, in contrast to the southwestern sector, which will register moderate precipitation increases. This, as part of climate change, will generate adverse conditions that will end up destroying the habitat and food source of pollinators, including honeybees.

The weight of the hive is determined by the time of the season and the phenology of the flowering plants, and the weight changes were associated with meteorological variables such as the duration of sunlight and air temperature (Czekońska et al., 2023). Therefore, it is necessary to implement mitigation measures for the imminent change that we will have in the highly suitable area, in which increases of up to 11.83 °C are reported.

The studies that use MCDA present limitations when trying to incorporate the floral resource as a criterion of land suitability for beekeeping, since they only use a LULC (agriculture) map as a parameter of the floral resource. However, both the spatial (distribution) and temporal (flowering phenology) elements of forage and agricultural species are key for beekeeping (Patel et al., 2023).

The floral resource is critical to sedentary and migratory beekeeping planning, as the installation or movement of hives to access a quality floral resource can be affected by a variety of environmental factors (e.g., climate change) and land management decisions that affect the availability and accessibility of the floral resource (Patel et al., 2020). Then, the availability and accessibility to quality floral resources determine the spatiotemporal mobility patterns and economic success of beekeepers (Castellanos-Potenciano et al., 2017). Therefore, future studies could improve the mapping of the floral resource to integrate it into an MCDA.

5. Conclusions

The apicultural suitability of the Amazonas region and its projection under two climate change scenarios were determined. The results indicate that 3.4 % (1417.90 km^2) of the territory is highly suitable for beekeeping, while 79.2 % (33,318.61 km^2) is moderately suitable, 17.2 % (7230.26 km^2) is marginally suitable, and 0.2 % (83.64 km^2) is not suitable. This suitability is mainly influenced by the average annual temperature, susceptibility to landslides, and access to floral resources, within the climatic, topographic, and environmental sub-criteria considered in this study.

The climate scenarios projected for the Amazonas region show changes in temperature and precipitation in areas highly suitable for beekeeping. While temperatures will increase in both scenarios SSP 2–4.5 and SSP 5–8.5, precipitation presents a mixed behavior, with decreases predominating in the north and increases in the southwest. These changes could directly affect current suitability conditions, especially in terms of the long-term sustainability of beekeeping in the region.

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CRediT authorship contribution statement

Darwin Gómez-Fernández: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ligia García:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Jhonsy O. Silva-López:** Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jaris Veneros Guevara:** Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Erick Arellanos Carrión:** Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rolando Salas-Lopez:** Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Malluri Goñas:** Validation, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **Nilton Atalaya-Marin:** Formal analysis, Data curation, Conceptualization. **Manuel Oliva-Cruz:** Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nilton B. Rojas-Briceño:** Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors 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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Data availability

The data used to support the conclusions of this study can be downloaded at the following link: https://next.data.4tu.nl/private_datasets/jmESCpYcD7dc3eTNb6VbXCWJ_xXVWYA_EHDVUjwdDog

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