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Land Suitability for Coffee (*Coffea arabica*) Growing in Amazonas, Peru: Integrated Use of AHP, GIS and RS

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Abstract: Peru is one of the world's main coffee exporters, whose production is driven mainly by five regions and, among these, the Amazonas region. However, a combined negative factor, including, among others, climate crisis, the incidence of diseases and pests, and poor land-use planning, have led to a decline in coffee yields, impacting on the family economy. Therefore, this research assesses land suitability for coffee production (*Coffea arabica*) in Amazonas region, in order to support the development of sustainable agriculture. For this purpose, a hierarchical structure was developed based on six climatological sub-criteria, five edaphological sub-criteria, three physiographical sub-criteria, four socio-economic sub-criteria, and three restrictions (coffee diseases and pests). These were integrated using the Analytical Hierarchy Process (AHP), Geographic Information Systems (GIS) and Remote Sensing (RS). Of the Amazonas region, 11.4% (4803.17 km^2), 87.9% (36,952.27 km^2) and 0.7% (295.47 km^2) are "optimal", "suboptimal" and "unsuitable" for the coffee growing, respectively. It is recommended to orient coffee growing in 912.48 km^2 of territory in Amazonas, which presents "optimal" suitability for coffee and is "unsuitable" for diseases and pests. This research aims to support coffee farmers and local governments in the region of Amazonas to implement new strategies for land management in coffee growing. Furthermore, the methodology used can be applied to assess land suitability for other crops of economic interest in Andean Amazonian areas.

Keywords: agricultural zoning; AHP-GIS; caficulture; EMC; land suitability; site selection

1. Introduction

In February 2020, world coffee exports (arabicas and robustas) reached 11.11 million bags (60 kg), higher than the 10.83 million bags exported in February 2019 [1]. Brazil is the world's leading coffee producer and exporter, boasting 2.1 million coffee-growing hectares and an average yield of 22 bags per hectare [2]. Peru, as a coffee exporter, stands in 12th place worldwide and 3rd place in South America [1]. Coffee is grown on approximately 425,416 ha in Peru, in 17 regions, employing more than 223,482 families [3]. The leading regions in Peruvian coffee production are Pasco, Cajamarca, San Martín, Junín and Amazonas, having an average annual yield of 1081 kg/ha, 1046 kg/ha, 969 kg/ha, 792 kg/ha and 705 kg/ha, respectively [4]. Although in February 2020, Peru exported 100,000 bags of coffee, 13,000 bags less than in February 2019 [5], Amazonas maintains the same production.

The decrease in coffee production around the world will be further accentuated in the future, mainly due to climate change [6]. The agricultural sectors of Latin America and the Caribbean are the most affected by climate change due to their high vulnerability [7]. For its part, the cultivation of coffee is sensitive to alterations and adverse climatic conditions, which interfere in the phenological process of coffee [8]. In addition, under climate change scenarios the incidence of diseases and pests can be much higher [9,10]. Another problem of the coffee activity is the deficient planning of the territory to establish potential lands for the cultivation of coffee. As a consequence, small producers cut down forests each year to install new coffee plots, causing disturbances in the ecosystem [11].

Therefore, one of the main alternatives for self-sufficiency agriculture consists in identifying land suitability for subsequent distribution on various types of sustainable agriculture [12,13]. The suitability analyses are based on the integration of Geographic Information Systems (GIS), Remote Sensing (RS) and Multicriteria Evaluation (MCE) techniques [14]. These analyses must be constantly updated in order to have more information on climate conditions and ensure the return on investments of producers [15]. The most widely used MCE technique is known as the Analytical Hierarchy Process (AHP) [16]. The AHP is used to solve complex decision-making processes, in which multiple criteria, sub-criteria and scenarios are involved, which are structured in hierarchies and the relative importance for each hierarchical group is weighed [16].

The integration of AHP, GIS and RS has been applied in various studies of land suitability, including, among others, wheat [17–19], coffee [20–23], maize [24,25], and other crops [26,27]. However, this integration requires environmental, socioeconomic and other criteria, as well as suitability thresholds that define the crop's optimal development. For this purpose, a group of experts provides information regarding coffee production, additionally; this group defines the importance of the criteria and sub-criteria, and unifies the information to be used in the analysis [28]. Specifically, for land suitability analysis on coffee, climatological, soil, physiographic and social criteria have been used [15,20,23,29]. In particular no studies, to our knowledge, have considered these techniques for land suitability on coffee in Peru, though, there is a report using only GIS and RS integration [30]. Likewise, in the Amazonas region, studies on land-use planning for agriculture are still few, however, it is worth mentioning the study on the Capacity for Increased Land Use (ILU) of the Ecological and Economic Zoning (ZEE), which focused mainly on crops in general [31].

This research analyses land suitability for coffee growing in the Amazonas region, in north-eastern (NE) Peru. For this purpose, (i) the criteria and sub-criteria that influence coffee development were identified and evaluated, (ii) the importance of the criteria and sub-criteria was hierarchized and weighted, (iii) the layers for each sub-criterion were elaborated, which (iv) were overlapped according to their weight of importance, including the study restrictions. The integration of the AHP, GIS and RS, allows an efficient analysis of land suitability and aims to guide the appropriate land-use management. In addition, it is intended to provide a methodological framework of potential application for crops of economic interest in Andean Amazonian areas.

2. Materials and Methods

2.1. Study Area

The Amazonas region is located in the north-eastern part of Peru (Figure 1, 3°0′–7°2′ S, and 77°0′–78°42′ W). It covers an area of 42,050.38 km^2 of rugged territory, covered mainly by the Amazon rainforest; the altitude ranges from 120 to 4400 m a.s.l and has a dominant warm humid climate. It also comprises two very marked sectors: The first sector, in the Andes, has an average annual temperature range between 7.4 and 19.8 °C, and the second sector, in the high jungle, has an average annual maximum temperature of 34.6 °C and a minimum of 10 °C. The region has entisol, inceptisol and ultisol soils [31,32]. Amazonas is one of the regions in the country with the greatest biophysical and sociocultural diversity, is notable for its agricultural activity (e.g., rice, coffee, cocoa, potatoes, yucca, bananas, etc.) and extensive cattle farming, and has an average of

8.3% illiteracy of agricultural producers [31]. Amazonas has a total population of 379,384 inhabitants (9.6 inh./km^2) [33] and is made up of the provinces of Bongará (3020.99 km^2), Chachapoyas (4507.01 km^2), Condorcanqui (17,873.82 km^2), Bagua (5861.16 km^2), Luya (3100.36 km^2), Utcubamba (3972.83 km^2) and Rodríguez de Mendoza (3714.24 km^2). These last four provinces are the main coffee producers, with approximately 34,000–42,744 hectares, producing around 25,000 tons per year, and with average yields ranging from 700 to 1250 kg/ha [31,34].

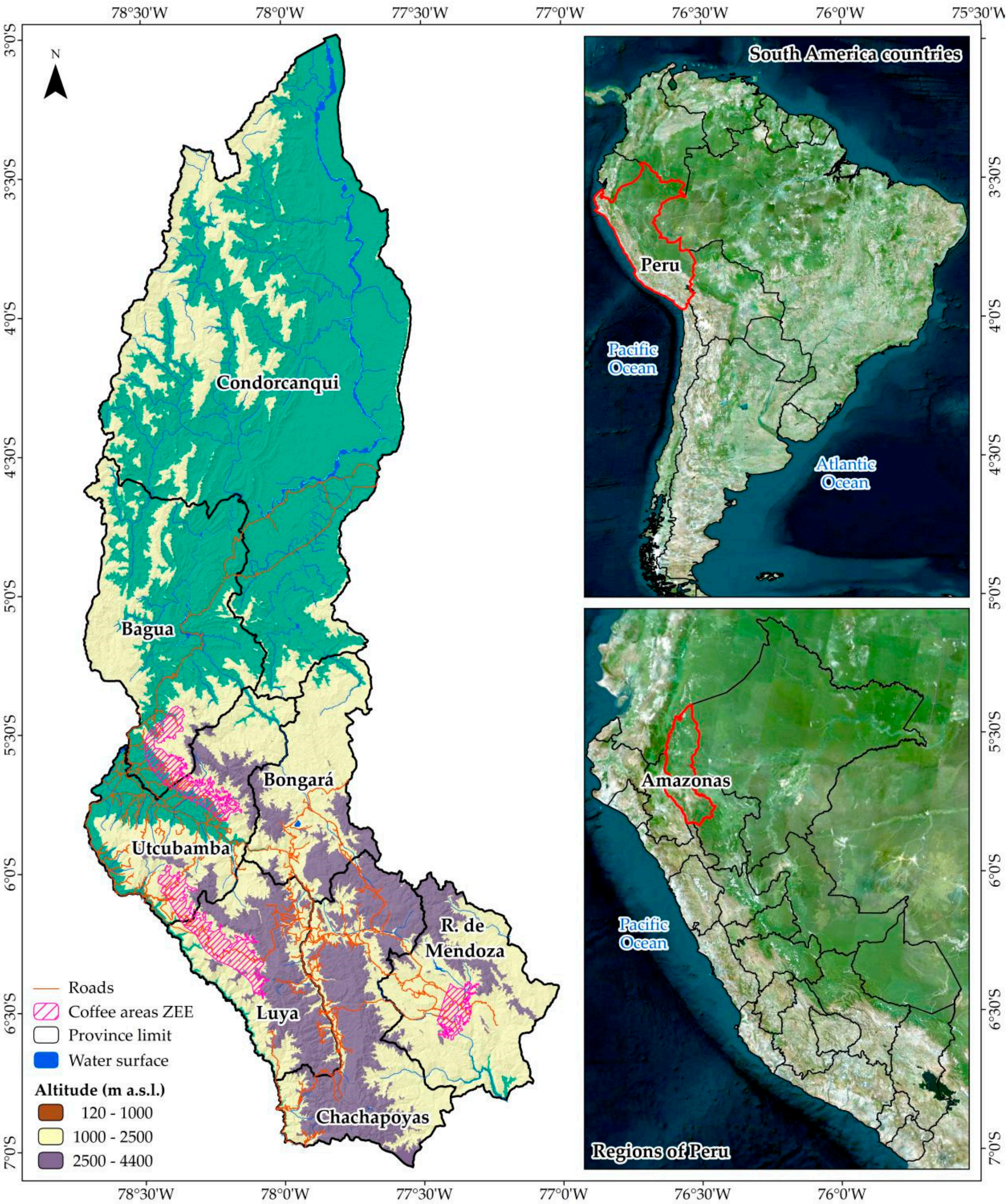

Figure 1. Geographical location of the Amazonas region, Peru.

2.2. Methodological Scheme

Figure 2 shows an analysis of coffee land suitability in Amazonas. In summary, (i) it identified and evaluated the climatological, soil, physiographic and socio-economic criteria as well as sub-criteria which influence on coffee growth, and (ii) it elaborated the layers with suitability thresholds for each sub-criterion, whilst also looking at (iii) the importance of the criteria and sub-criteria, which was prioritized and weighted using Pairwise Comparison Matrices (PCMs), and (iv) the maps were overlapped based on the importance weights, and finally (v) the suitability map was restricted to the conditions regarding coffee diseases and pests (restrictions).

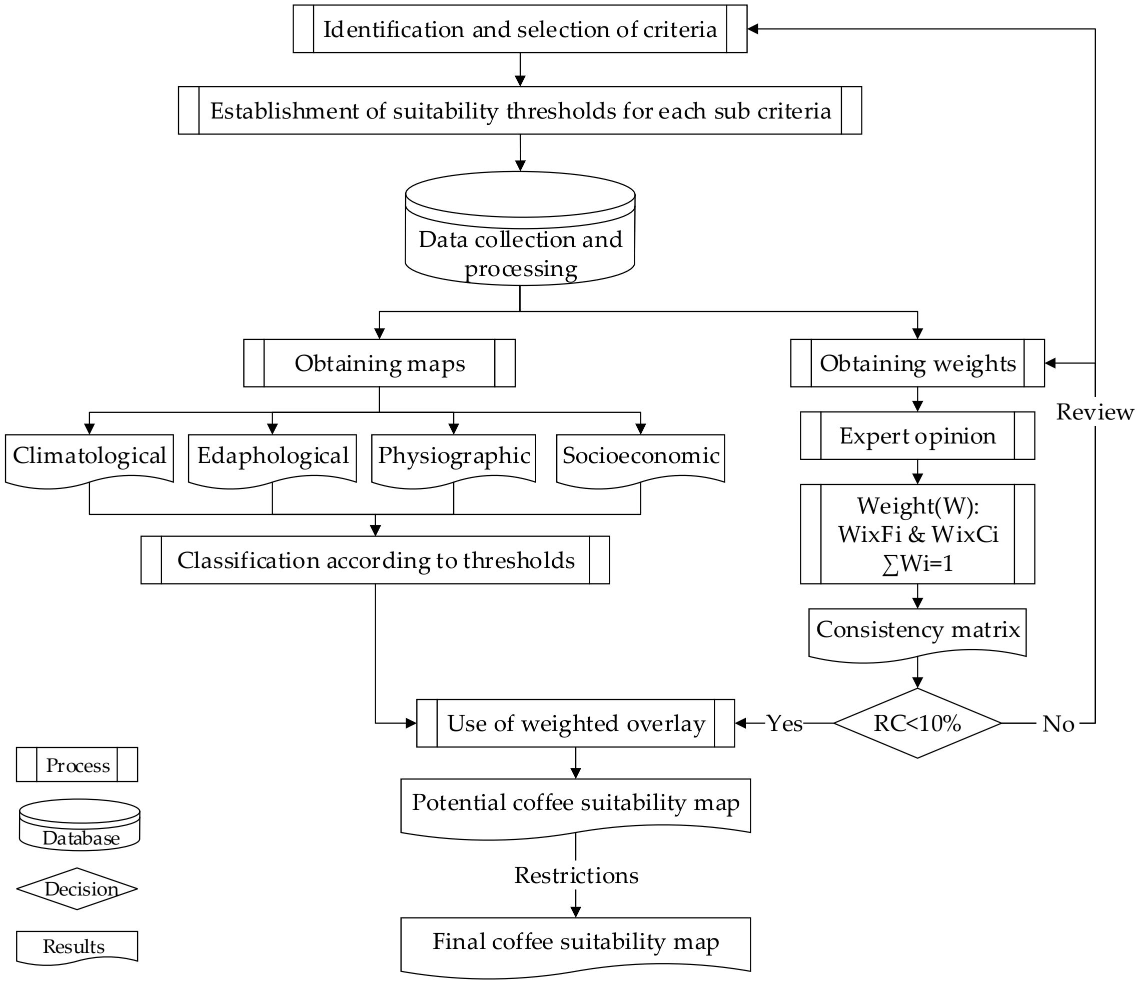

Figure 2. Flow chart of the methodology used for the analysis of the suitability of the territory for coffee growing in the Amazonas region, Peru.

2.3. *Identification and Selection of Criteria, Sub-Criteria and Restrictions*

Based on a bibliographic review, the main criteria and sub-criteria that determine the development of coffee growing in Peru and the world were identified [35–38]. For a detailed description of Arabica coffee and its cultivation, see Kuit et al. [39]. A hierarchy, therefore, was constructed based on 4 criteria (climatological, edaphological, physiographic and socioeconomic) which in turn are broken down into 18 sub-criteria (Figure 3). Accordingly, as Climatological sub-criteria, we have considered the following sub-criteria: average annual temperature, annual mean minimum temperature, annual mean maximum temperature, mean annual rainfall, relative humidity and dry periods; as Edaphological sub-criteria, pH, Texture, Stoniness, Soil Organic Matter (SOM) and Cation Exchange Capacity (CEC); in the same way, as Physiographic sub-criteria: Elevation, Terrain slope and Terrain aspect; and finally, as Socioeconomic sub-criteria: Land Use/Land Cover (LULC), distance to the road network, distance to the water network and Protected Natural Areas (PNA). Furthermore, to apply a principle of prevention, the map of potential land suitability was restricted by layers of the most common diseases and pests of coffee growing in Amazonas [40]. Such layers were based on optimal temperature for the development of coffee leaf rust (*Hemileia vastatrix*), coffee berry borer (*Hypothenemus hampei*) and leaf spot (*Cercospora coffeicola*).

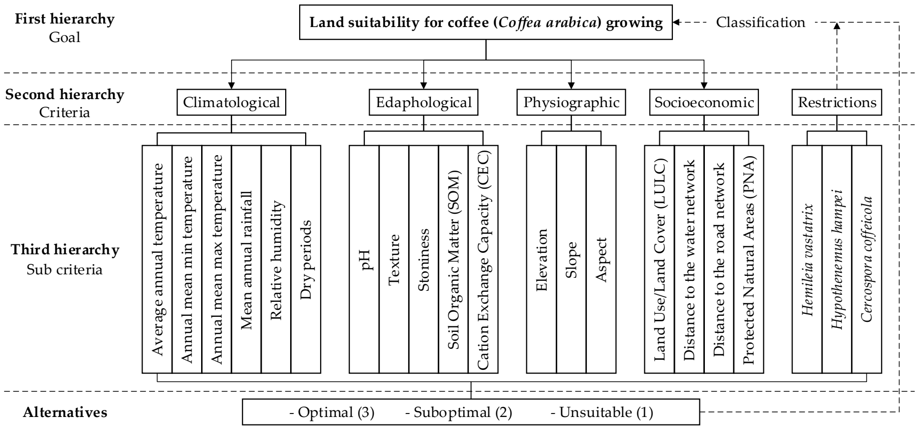

Figure 3. Hierarchical structure of criteria and sub-criteria considered in the analysis of coffee suitability in the Amazonas region, Peru.

The sub-criteria were reclassified and weighted, according to suitability thresholds of the territory, in three categories [20]: "Optimal" (3), "Suboptimal" (2) and "Unsuitable" (1) (Table 1). We considered the same categories for the restrictions; the "optimal" category for diseases or pests resulted in being "unsuitable" for coffee.

Table 1. Sub-criteria suitability thresholds (requirements) and restrictions for coffee growing in the Amazonas region, Peru.

Sub-Criteria/Criteria	Optimal (3)	Suboptimal (2)	Unsuitable (1)	Adapted From
		Climatological		
Average annual temperature (°C)	18–23	15–18; 23–26	>26; <15	[20–22,41,42]
Annual mean min temperature (°C)	>18	10–18	<10	[43,44]
Annual mean max temperature (°C)	<25	25–30	>30	[45]
Mean annual rainfall (mm)	1600–1800	1100–1600; 1800–2000	<1100; >2000	[4,46–49]
Relative humidity (%)	70–90	65–70	<65; >90	[22,42]
Dry periods (%)	80–100	40–80	0–40	[50]
		Edaphological		
pH	5–6.5	4.5–5; 6.5–7.5	<4.5; >7.5	[4,51,52]
Texture (texture class) [1]	L, SCL, SiCL	CL, SL, SC, SiL, SiC	S, C, Si, LS	[53,54]
Stoniness (%)	0–6	6–15	<15	[55,56]
SOM (%)	>3	2–3	<2	[4,57]
CEC (cmol+/Kg)	>25	15–25	<15	[58]
		Physiographic		
Elevation (m a.s.l.)	1400–1800	900–1400; 1800–2500	<900; >2500	[4,20,23]
Terrain slope (%)	0–12	12–25	>25	[59,60]
Terrain aspect	N, NE, NW	E, W	S, SW, SE	[61]
		Socioeconomic		
LULC [2]	40	20	30, 50, 60, 80, 90, 112, 114, 116, 122, 124, 126	[62,63]
Distance to water network (km)	0–1	1–5	>5	[62,63]
Distance to road network (km)	0–2	2–5	>5	[62,63]
PNA	Out	Buffer zone	Within	[64]
		Annual mean temperature conditions (°C) for diseases and pests		
Coffee leaf rust (*H. vastatrix*)	22–26	17–22	<17; >26	[65,66]
Coffee berry borer (*H. hampei*)	>21	18–21	<19	[67]
Leaf spot (*C. coffeicola*)	22–30	19–22	<19; >30	[68]

[1] L: Loam, SCL: Sandy clay loam, SiCL: Silty clay loam, CL: Clay loam, SL: Sandy loam, SC: Sandy clay, SiL: Silt loam, SiC: Silty clay, S: Sand, C: Clay, Si: Silt, LS: Loamy sand. [2] LULC typologies correspond to the Copernicus Global Land Map [69]: 40: Cropland, 20: Shrubs, 30: Herbaceous vegetation, 50: Urban/built up, 60: Bare/sparse vegetation, 80: water bodies, 90: Herbaceous wetland, and >100: all the forests.

2.4. Resources and Mapping

Data on geographic information for climatological sub-criteria and for disease and pest restrictions, with the exception of relative humidity and dry periods, were obtained from WorldClim 2.1, with average data from 1970 to 2000 and a resolution of ~1 km [70]. The Relative Humidity (RH) layer was generated on the Google Earth Engine (GEE) platform. This platform is freely accessible, works using the Google cloud, and is capable of processing petabytes of geospatial data on a global scale [71]. GEE contains climate data (evaporation, humidity, temperature, etc.) from the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) GEE at 0.1° spatial resolution [72,73]. A script using JavaScript coding language was implemented to develop Equation (1) using the required bands as input data. The RH (Equation (1)) was calculated as the quotient between the current pressure (e) and the air saturation pressure (e_s) at an air temperature T (in Kelvin), e_s is the full denominator of Equation (1). This equation was derived from Claysius Clayperon's law.

$$RH = \left(\frac{e}{6.11^{\left(\frac{17.27(T\ -\ 273)}{T\ -\ 36}\right)}} \right) \times 100 \tag{1}$$

The dry periods layer was based on methodology used to quantify meteorological droughts [74]. Therefore, the total annual average rainfall data was divided into five quintiles. Values in the first two quintiles 0–20% and 20–40% are considered dry and "unsuitable", values between 40–80% are considered "suboptimal" and values in the last quintile (80–100%) are considered wet or "optimal".

The data for the edaphological sub-criteria were obtained from system for global digital soil mapping SoilGrids, with a spatial resolution of 250 m [75]. The layers of the depths 0–5 cm, 5–10 cm, and 10–15 cm were all averaged out, given that the first 20cm has the highest concentration of coffee roots [76]. The SOM layer was obtained from the product of the Soils Organic Carbon in percentage (SOC%) and a conversion factor of 1.72 [77,78]. SOC% was obtained by converting the Organic Carbon layer into Ton/ha (SOC) of SoilGrids using Equation (2), where dap is the bulk density of the soil (g/cm^3) and SD is the sampling depth (cm).

$$\text{SOC\%} = \text{SOC}/dap \times SD \times 1000 \tag{2}$$

The slope and aspect of the terrain were derived from the 30-m spatial resolution digital elevation model (DEM) from NASA's Shuttle Radar Surveying Mission (SRTM) [79], by using the "slope" and "aspect" tools of QGIS 3.10. The same DEM was reclassified to obtain the elevation suitability map. Regarding the socioeconomic criterion, a raster layer downloaded from The Copernicus Global Land Service (CGLS) was used for the LULC sub-criterion, at a spatial resolution of 100 m [69]. This layer was complemented with the agricultural LU polygons of the LULC map of the ZEE [31] for Amazonas and of Rojas et al. [80] for R. de Mendoza. The distance to the road network was generated using the 2018 national, departmental and neighborhood road network layers downloaded from the Ministry of Transport and Communications (MTC) [81]. The distance to the water network was generated using the IGN's river and stream layer [82]. These last two sub-criteria were updated to 2020 based on a Google Satellite server image as a basemap, using the QGIS 3.10 on-screen digitizing method. Additionally, we used the PNA and their buffer zones updated to 2020 by the National Service of Natural Areas Protected by the State (SERNANP) [83].

The climatological, edaphological, physiographic, socioeconomic and restriction sub criteria were extracted according to the geographical limit of the study area. Subsequently, they were reclassified in the three suitability thresholds (see Table 1), using the simple reclassify values tool of SAGA in QGIS 3.10 and were re-scaled to 30 m pixels, so as to homogenize the geospatial data, using the resampling tool.

2.5. Multiple Criteria Evaluation (MCE) and Analytical Hierarchy Process (AHP)

A PCM was constructed to compare and weight the criteria to each other for each hierarchical group (see Figure 3), and, in addition, a PCM was constructed to compare and weight diseases and pests. The construction of the aforementioned PCMs was based on the weighting scale proposed by Saaty [84] (Table 2). For each set of criteria, a group of 10 coffee growing experts assigned a weighted value. This group of experts was made up of national and international researchers in coffee cultivation, as well as professionals from the agricultural coffee cooperatives in the region.

Table 2. Weighting scale for pair comparison matrices based on Saaty [84].

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
Minimal		Very weak		Weak		Slightly weak		Equal importance	Moderate		Strong		Very strong		Extreme	
Least important									Most important							

The PCM provided by the expert group were processed (for an example of PCM matrix processing, see [85]), which allows to us to obtain the weight of importance of each of the criteria and sub-criteria; the sum of weights should always be 1 per hierarchical group [85]. Because the PMCs of the experts may have inconsistencies, the inconsistency values that may be acceptable are calculated using the Consistency Ratio (*CR*) [84]. Therefore, it was considered that in a PCM, the highest eigenvalue (λmax) is always greater than or equal to the number of rows and columns (n) of the PCM, therefore we can calculate the Consistency Index (*CI*) using Equation (4) [86]. Then, *CR* is calculated as the quotient between the *CI* and the Random Consistency Index (*RI*) [84]. The RI values are conditioned by the "n" value of the matrix, shown in Table 3.

$$CI = (\lambda max - n)/(n - 1) \tag{3}$$

Table 3. *RI* values based on the "n" of the matrix according to Saaty [86].

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

In order for the consistency of the matrix to be considered as acceptable, the *CR* must be less than 0.1; otherwise, the AHP may give erroneous results unless the assigned values in Table 1 are re-examined by the coffee-growing experts [87–90]. All of the above calculations were performed using the Easy AHP plugin in QGIS 2.8. Thereafter, each weighting (importance) of the sub-criteria was multiplied by its respective weight, obtaining a local score, which was multiplied by the weight of each criteria (climatological, edaphological, physiographic and socioeconomic) to obtain the global score and identify the most important criteria. We proceeded using a similar method for diseases and pests of coffee growing.

2.6. Obtaining Sub-Models and Suitability Model for Coffee Growing

With the weighted weights calculated and the reclassified maps, the ArcMap 10.5 Weighted Overlay tool was used to obtain the sub-models of climatological, edaphological, physiographic, socioeconomic and disease and pest suitability. At the same time, the first four sub-models were integrated with the same tool to generate the final suitability model for coffee cultivation. This final model was then overlaid with the disease and pest sub-model to identify the territory with these phytosanitary restrictions. Furthermore, the "optimal" plots for coffee, which at the same time are "unsuitable" and "suboptimal" for diseases and pests, were counted according to their area: 0.5–1 ha, 1–2 ha, 2–3.5 ha, 3.5–5 ha and >5 ha. These ranges were established considering that coffee cultivation in the Amazonas region is practiced mainly in plots < 1 ha (family and subsistence agriculture) [91]. Plots < 0.5 ha were considered insufficient to be economically viable. Finally, to validate the final suitability model, it was compared with the spatial distribution of the coffee areas of the ZEE (Figure 1) [31] and with farms georeferenced by the coffee cooperatives and by the Research Institute for the Sustainable Development of Ceja de Selva (INDES-CES) of the Toribio Rodríguez National University of Mendoza (UNTRM). For this, it was assumed that the distribution of current coffee areas is the result of a historical and technical selection for the best possible available area [20].

3. Results

3.1. Criteria Weighting for the Analysis of Land Suitability

Table 4 shows the weightings obtained for each sub-criterion, based on the estimates of 10 coffee growing experts. The most important sub-criteria for establishing coffee growth were elevation (13.27%), followed by LULC (8.18%). On the other hand, the least important were relative humidity (3.16%) and annual mean minimum temperature (2.69%). When taking the criteria into account, we found that the following sub-criteria obtained the highest value for each criterion group: average annual temperature (22.37%), pH (29.22%), elevation (53.06%) and LULC (32.72%), whereas, the lowest weightings were given to the annual mean minimum temperature (10.76%), SOM (16.32%), aspect of the land (22.75%) and distance to water network (20.22%). Regarding restrictions, *H. Vastatrix* was the most important (46.7%), followed by *H. hampei* (32.0%) and *C. coffeicola* (21.2%).

Table 4. General weighting of criteria and sub-criteria for land suitability analysis regarding coffee growing in the Amazonas region, Peru.

Criterion	Weight (%)	Rank	Sub-Criterion	Rank	Weight (%)	Standardized Weight (%)	Standardized Rank
Climatological	28.31	2	Average annual temperature	1	22.37	5.59	5
			Annual mean min temperature	6	10.76	2.69	18
			Annual mean max temperature	4	15.28	3.82	16
			Mean annual rainfall	2	21.4	5.35	9
			Relative humidity	5	12.65	3.16	17
			Dry periods	3	17.56	4.39	13
Edaphological	25.03	3	pH	1	29.22	7.31	3
			Texture	2	19.06	4.77	11
			Stoniness	4	16.60	4.15	14
			SOM	5	16.32	4.08	15
			CEC	3	18.80	4.70	12
Physiographic	18.31	4	Elevation	1	53.06	13.27	1
			Slope	2	24.18	6.05	5
			Aspect	3	22.75	5.69	6
Socioeconomic	28.35	1	LULC	1	32.72	8.18	2
			Distance to water network	4	20.22	5.06	10
			Distance to road network	3	21.94	5.49	8
			PNAs	2	25.12	6.28	4
Coffee diseases and pests			*H. vastatrix*	1	46.70	46.70	
			H. hampei	2	32.00	32.00	
			C. coffeicola	3	21.20	21.20	

3.2. Sub-Criteria Maps Generated According to Land Suitability Thresholds

Figure 4 shows the reclassified maps for each of the climatological, edaphological, physiographic and socioeconomic sub-criteria, according to suitability thresholds (Table 1). Meanwhile, Figure 5 presents the land's suitability for diseases and pests. Furthermore, Table 5 provides the areas for each sub-criteria suitability threshold and diseases and pests. Accordingly, the sub-criteria with the greatest "high suitability" area in relation to their criteria group included: relative humidity (81.8%), SOM (92.8%), aspect of the land (43.9%) and PNA (70.9%). Conversely, the ones with the largest "not suitable" area were: rainfall (59.0%), CEC (25.2%), elevation (55.6%) and LULC (76.4%). Hence, the SOM is the sub-criterion that most favours coffee growth, while the LULC is in fact the sub-criterion that most restricts the territory. Regarding restrictions, *H. vastatrix* has the largest area (56.6%) that is suitable for its development in Amazonas; on the contrary, *H. hampei* has the smallest area (37.6%).

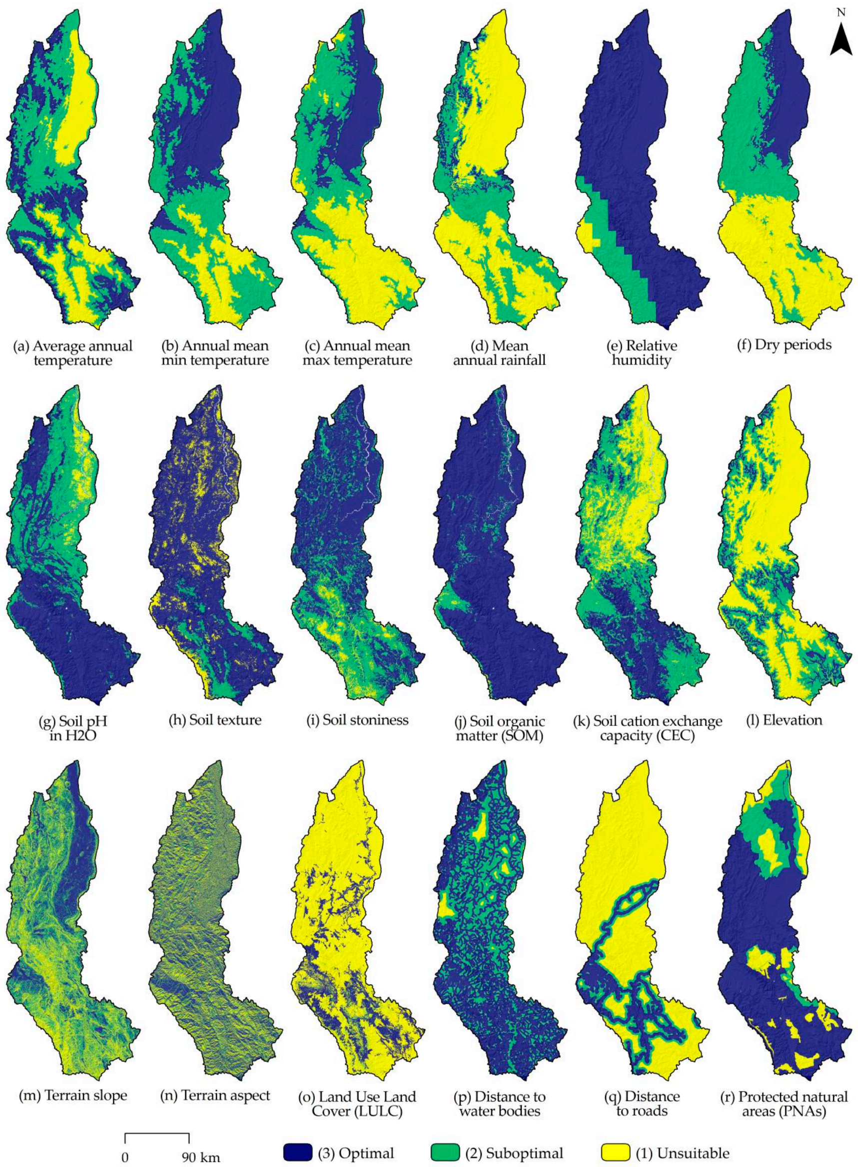

Figure 4. Suitability map of the climatological (**a**–**f**), edaphological (**g**–**k**), physiographic (**l**–**n**) and socioeconomic (**o**–**r**) sub-criteria for coffee growth in the Amazonas region, Peru.

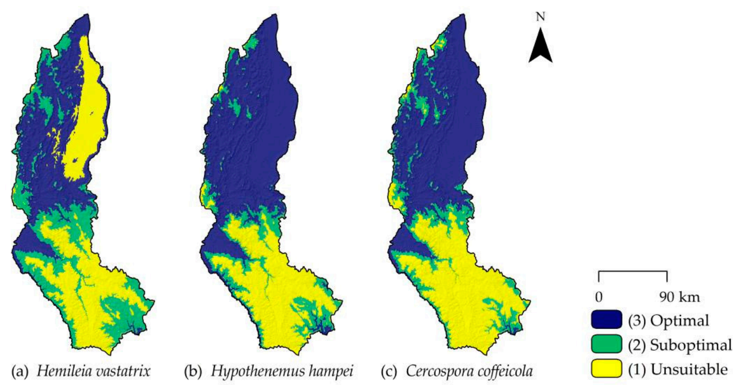

Figure 5. Suitability maps for coffee diseases and pests in the Amazonas region, Peru.

Table 5. Suitability area for sub-criteria and restrictions for coffee growing in the Amazonas region, Peru.

Criteria	Sub-Criteria	Unsuitable (1)		Suboptimal (2)		Optimal (3)	
		km^2	%	km^2	%	km^2	%
Climatological	Average annual temperature	11,288.36	26.8%	18,820.54	44.8%	11,941.44	28.4%
	Annual mean min temperature	15,327.46	36.5%	16,004.79	38.1%	10,718.09	25.5%
	Annual mean max temperature	6560.06	15.6%	18,396.65	43.7%	17,093.63	40.7%
	Mean annual rainfall	24,823.10	59.0%	14,909.98	35.5%	2317.26	5.5%
	Relative humidity	961.53	2.3%	6691.22	15.9%	34,397.59	81.8%
	Dry periods	17,030.31	40.5%	15,581.36	37.1%	9438.67	22.4%
Edaphological	pH	1952.54	4.6%	15,700.48	37.3%	24,397.35	58.1%
	Texture	5220.09	12.4%	3206.76	7.6%	33,623.52	80.0%
	Stoniness	2508.18	6.0%	14,451.71	34.4%	25,090.48	59.7%
	SOM	323.33	0.8%	2724.96	6.5%	39,002.08	92.8%
	CEC	10,587.31	25.2%	18,945.12	45.1%	12,517.94	29.8%
Physiographic	Elevation	23,272.66	55.6%	14,455.07	34.5%	4322.61	10.3%
	Slope	11,601.59	27.7%	17,004.65	40.6%	13,444.10	32.1%
	Aspect	13,846.48	33.1%	9824.54	23.5%	18,379.31	43.9%
Socioeconomic	LULC	32,124.14	76.4%	969.22	2.3%	8957.02	21.3%
	Distance to water network	1043.89	2.5%	14,035.28	33.4%	26,971.21	64.1%
	Distance to road network	29,454.62	70.0%	5208.86	12.4%	7386.86	17.6%
	PNAs	6005.71	14.3%	6246.28	14.9%	29,798.38	70.9%
Coffee diseases and pests	*H. vastatrix*	11,972.41	28.5%	6287.24	15.0%	23,790.69	56.6%
	H. hampei	15,287.29	36.4%	10,933.68	26.0%	15,829.36	37.6%
	C. coffeicola	14,147.37	33.6%	6570.14	15.6%	21,332.83	50.7%

3.3. Suitability Sub-Model (Criteria) Maps

With the weighted overlap of sub-criteria, the suitability sub-models were generated for each hierarchical group (Figure 6). The results demonstrate that the edaphological sub-model (60.75%) has the largest "optimal" area for coffee cultivation in Amazonas (Table 6). Nevertheless, the climatological sub-model (3.43%) has the smallest "optimal" area. Most importantly, 37.64% (15,859.40 km^2) of Amazonas is not suitable for coffee cultivation, due to its "optimal" conditions for the development of diseases and pests.

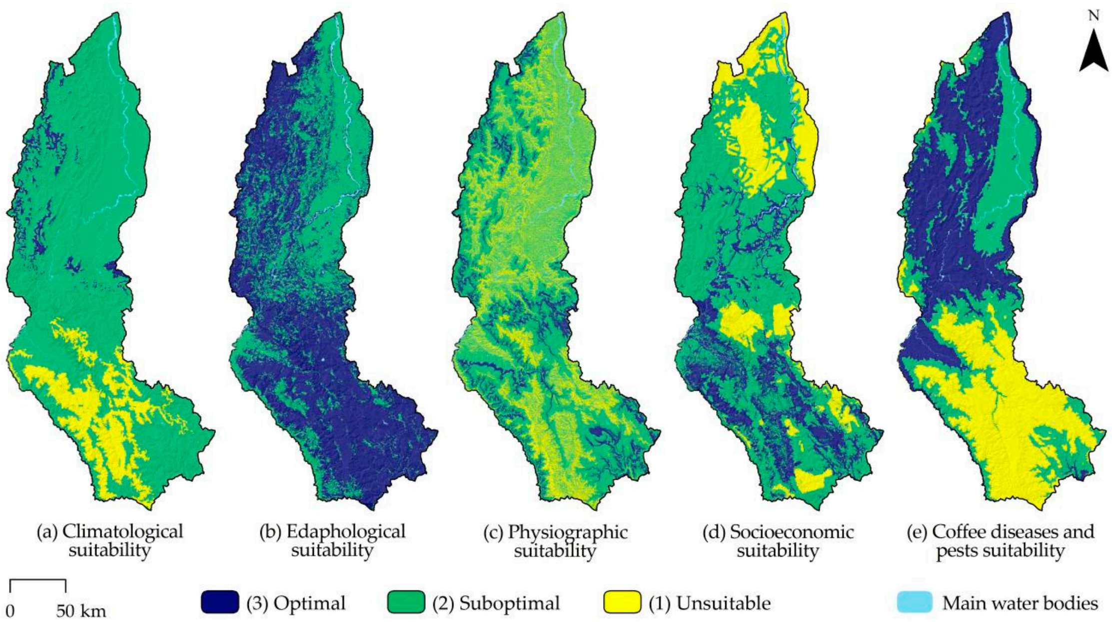

Figure 6. Suitability map (**a**) Climatological, (**b**) Edaphological, (**c**) Physiographic, (**d**) Socioeconomic, and (**e**) Coffee growing diseases and pests in the Amazonas region, Peru.

Table 6. Suitability area of sub-model for coffee cultivation in the Amazonas region, Peru.

Criteria	Unsuitable (1)		Suboptimal (2)		Optimal (3)	
	km^2	%	km^2	%	km^2	%
Climatological	5821.57	13.84	34,787.52	82.73	1441.25	3.43
Edaphological	195.94	0.47	16,306.93	38.78	25,547.50	60.75
Physiographic	10,844.19	25.79	28,027.54	66.65	3178.6	7.56
Socioeconomic	7951.14	18.91	25,819.26	61.40	8278.79	19.69
Coffee diseases and pests	11,972.41	28.47	14,248.57	33.88	15,829.40	37.64

3.4. Land Suitability Models for Coffee Growing

With the weighted superposition of climatological, edaphological, physiographic and socioeconomic sub-models, we generated the model of land suitability for coffee growing (Figure 7a). In fact, in Amazonas, 11.4% (4803.17 km^2), 87.9% (36,952.27 km^2) and 0.7% (295.47 km^2) are "optimal", "suboptimal" and "unsuitable", respectively, for coffee growing (Table 7). At the provincial level, Rodríguez de Mendoza (1130.93 km^2), Bagua (913.99 km^2) and Condorcanqui (913.90 km^2) present the largest areas with "optimal" suitability for coffee growing, while Luya (295.73 km^2) and Chachapoyas (282.70 km^2) present the least "optimal" areas. Then, with the weighted superposition of the territory suitability model for coffee growing (Figure 7a) and the suitability sub-model for diseases and pests (Figure 6e), the territory suitability model for coffee cultivation with restrictions was generated (Figure 7b). It was found that, 7.6% (1208.18 km^2), 18.6% (2628.00 km^2) and 8.0% (966.92 km^2) of the "optimal", "suboptimal" and "unsuitable" territory, respectively, for the development of diseases and pests, is "optimal" for growing coffee. At the provincial level, Condorcanqui (10,217.15 km^2) and Bagua (4059.37 km^2) present the largest areas with "optimal" suitability for the development of diseases and pests, while Luya (71.38 km^2) and Chachapoyas (15.83 km^2) present the least "optimal" areas. Of the territory of the Amazonas region, 6.25% (2628.00 km^2) is considered "very optimal", since it has "optimal" suitability for coffee and "suboptimal" suitability for diseases and pests, while 2.30% (966.92 km^2) is considered "excellent", since it has "optimal" suitability for coffee and is "unsuitable" for diseases and pests.

Table 7. Area of the suitability model for coffee growing and percentage of area that is covered by the suitability of the restrictions, according to provinces in Amazonas region, Peru.

Province/Region	Suitability for Growing Coffee			Area (%) Covered by the Suitability of the Restrictions					
				Optimal (3)		Suboptimal (2)		Unsuitable (1)	
	level	km^2	%	km^2	%	km^2	%	km^2	%
Bagua	Optimal (3)	913.99	15.6	640.02	15.8	268.82	19.1	5.15	1.3
	Suboptimal (2)	4935.27	84.2	3419.35	84.2	1140.62	80.9	375.26	95.6
	Unsuitable (1)	11.95	0.2	0.00	0.0	0.00	0.0	11.95	3.0
	Total	5861.20	100.0	4059.37	100.0	1409.44	100.0	392.35	100.0
Bongará	Optimal (3)	539.96	17.9	10.54	6.2	173.22	15.0	356.20	21.0
	Suboptimal (2)	2465.92	81.6	159.78	93.8	982.27	85.0	1323.87	78.1
	Unsuitable (1)	15.12	0.5	0.00	0.0	0.00	0.0	15.12	0.9
	Total	3020.99	100.0	170.32	100.0	1155.49	100.0	1695.18	100.0
Chachapoyas	Optimal (3)	282.70	6.3	0.00	0.0	20.63	5.4	262.07	6.4
	Suboptimal (2)	4199.83	93.2	15.83	100.0	359.14	94.6	3824.76	93.0
	Unsuitable (1)	24.58	0.5	0.00	0.0	0.00	0.0	24.58	0.6
	Total	4507.11	100.0	15.83	100.0	379.77	100.0	4111.40	100.0
Condorcanqui	Optimal (3)	913.90	5.1	378.96	3.7	534.89	7.2		0.0
	Suboptimal (2)	16,795.54	94.0	9836.85	96.3	6854.64	92.7	104.05	39.7
	Unsuitable (1)	164.43	0.9	1.34	0.0	4.82	0.07	158.27	60.3
	Total	17,873.87	100.0	10,217.15	100.0	7394.36	100.0	262.32	100.0

Table 7. *Cont.*

Province/Region	Suitability for Growing Coffee			Area (%) Covered by the Suitability of the Restrictions					
				Optimal (3)		Suboptimal (2)		Unsuitable (1)	
	level	km^2	%	km^2	%	km^2	%	km^2	%
Luya	Optimal (3)	295.73	9.5	0.74	1.0	250.81	38.3	44.18	1.9
	Suboptimal (2)	2800.44	90.3	70.63	99.0	403.76	61.7	2326.01	98.0
	Unsuitable (1)	4.22	0.1	0.00	0.0	0.04	0.0	4.18	0.2
	Total	3100.39	100.0	71.38	100.0	654.61	100.0	2374.36	100.0
Rodríguez de Mendoza	Optimal (3)	1130.93	30.4	26.81	27.7	817.78	48.5	286.33	14.8
	Suboptimal (2)	2557.60	68.9	70.02	72.3	868.90	51.5	1618.45	83.8
	Unsuitable (1)	25.94	0.7	0.00	0.0	0.00	0.0	25.94	1.3
	Total	3714.47	100.0	96.83	100.0	1686.68	100.0	1930.72	100.0
Utcubamba	Optimal (3)	725.96	18.3	151.11	12.9	561.85	39.5	13.01	0.9
	Suboptimal (2)	3197.67	80.5	1022.06	87.1	862.30	60.5	1313.27	95.5
	Unsuitable (1)	49.24	1.2	0.15	0.0	0.00	0.0	49.09	3.6
	Total	3972.87	100.0	1173.32	100.0	1424.15	100.0	1375.36	100.0
Total For Amazonas	Optimal (3)	4803.17	11.4	1208.18	7.6	2628.00	18.6	966.92	8.0
	Suboptimal (2)	36,952.27	87.9	14,594.52	92.3	11,471.63	81.3	10,885.68	89.7
	Unsuitable (1)	295.47	0.7	1.49	0.01	4.86	0.03	289.11	2.4
	Total	42,050.40	100.0	15,804.19	100.0	14,104.50	100.0	12,141.71	100.0

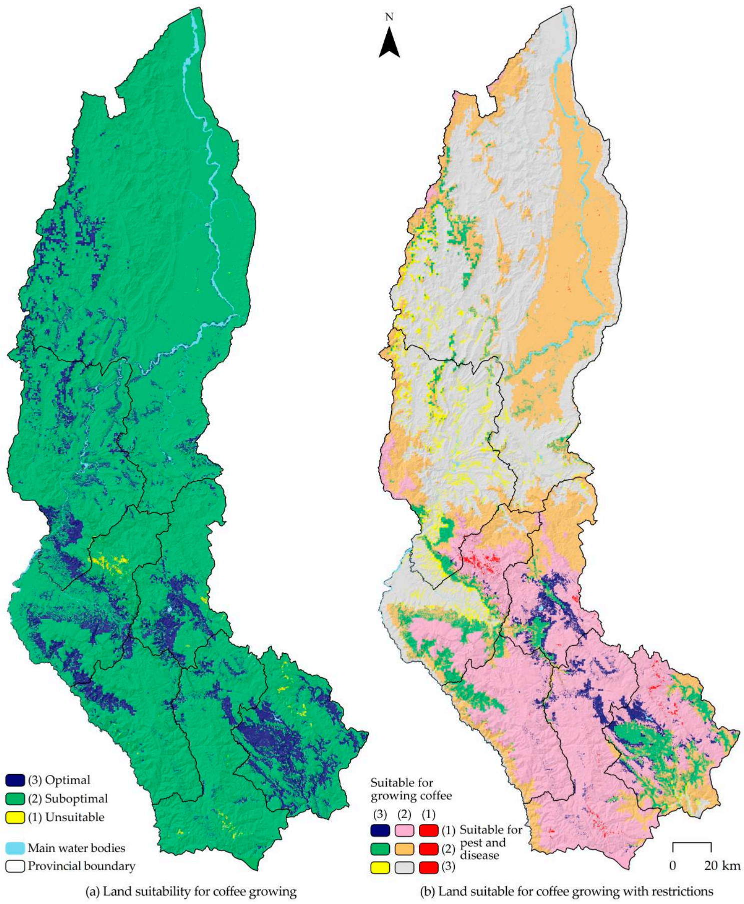

Figure 7. Suitability map of the territory for coffee production: (**a**) without restrictions and (**b**) with restrictions due to diseases and pests in the Amazonas region, Peru.

Of the "very optimal" and "excellent" territory for coffee cultivation, 0.3% (3.17 km^2) and 0.1% (2.52 km^2), respectively, have plots with areas < 0.5 ha, so they are not large enough to be economically viable (Table 8). In addition, 75.05–98.90% of both "very optimal" and "excellent" plots have surfaces > 10 ha, in all provinces.

Table 8. Area of "very optimal" (VO) and "excellent" (Ex) plots for coffee, according to provinces in the Amazonas region, Peru.

Province/Region	Suitability	0.5–1 ha		1–2 ha		2–3.5 ha		3.5–5 ha		5–10 ha		>10 ha	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Bagua	Ex	0.02	0.3	0.09	1.7	0.0	0.0	0.08	1.5	0.16	3.0	4.82	93.6
	VO	0.42	0.2	0.52	0.2	0.4	0.1	0.52	0.2	1.88	0.7	264.72	98.5
Bongará	Ex	0.76	0.2	1.53	0.4	0.95	0.3	0.82	0.2	2.99	0.8	348.61	97.9
	VO	0.18	0.1	0.56	0.3	0.47	0.3	0.45	0.3	0.98	0.6	170.52	98.4
Chachapoyas	Ex	2.90	1.1	5.41	2.1	4.12	1.6	3.66	1.4	6.85	2.6	237.46	90.6
	VO	0.16	0.8	0.35	1.7	0.58	2.8	0.46	2.2	1.31	6.4	17.72	85.9
Condorcanqui	Ex	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0
	VO	2.07	0.4	3.70	0.7	6.95	1.3	8.86	1.7	16.59	3.1	495.58	92.7
Luya	Ex	1.40	3.2	2.76	6.3	1.76	4.0	1.16	2.6	3.13	7.1	33.16	75.1
	VO	0.41	0.2	1.29	0.5	0.97	0.4	0.93	0.4	2.12	0.8	245.07	97.7
Rodríguez de Mendoza	Ex	0.45	0.2	0.83	0.3	1.76	0.6	1.58	0.6	4.58	1.6	277.15	96.8
	VO	0.29	0.0	0.78	0.1	1.36	0.2	1.82	0.2	4.11	0.5	808.79	98.9
Utcubamba	Ex	0.22	1.7	0.36	2.8	0.28	2.2	0.26	2.0	0.41	3.1	11.28	86.7
	VO	0.98	0.2	4.67	0.8	3.19	0.6	3.04	0.5	6.43	1.1	543.28	96.7
Total for Amazonas	Ex	5.75	0.6	10.99	1.1	8.86	0.9	7.56	0.8	18.11	1.9	912.48	94.4
	VO	4.51	0.2	11.88	0.5	13.90	0.5	16.08	0.6	33.43	1.3	2545.68	96.9

The results of the validation show that there is a close correspondence between the patterns of the areas modeled as "optimal" for the cultivation of coffee and the coffee areas of the ZEE and the farms georeferenced by the coffee cooperatives and by the INDES-CES of the UNTRM (Figure 8).

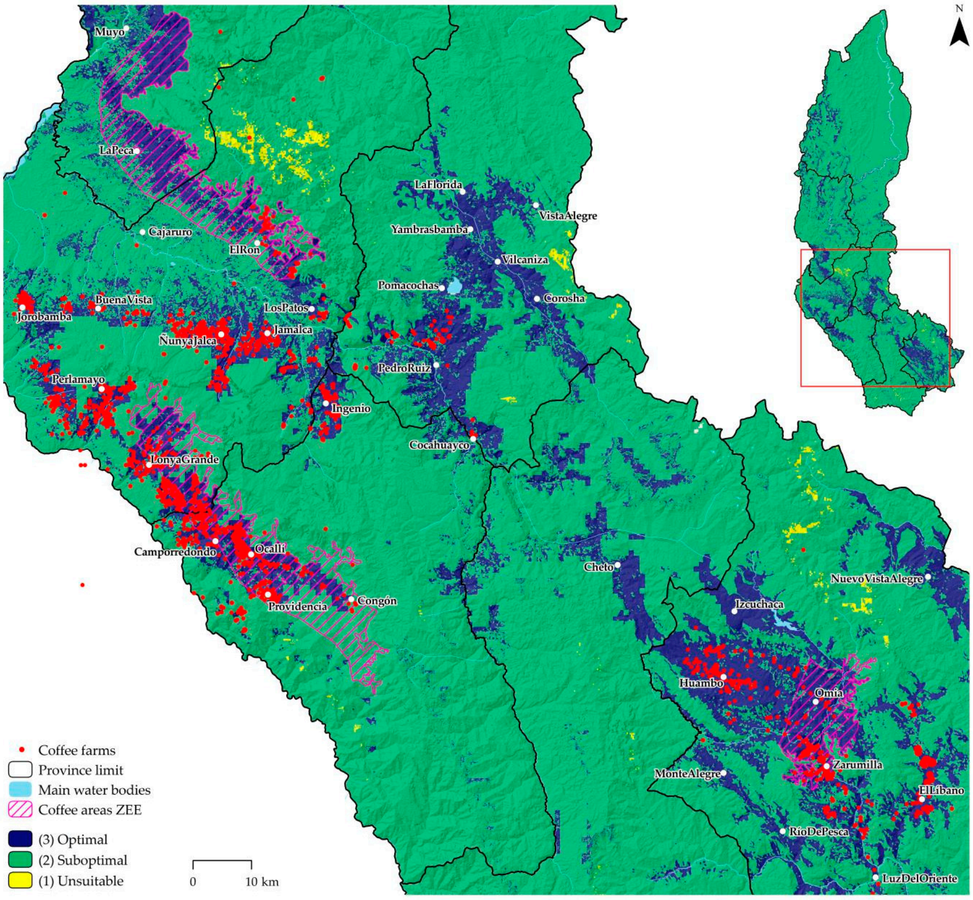

Figure 8. Current coffee growing areas and land suitability modeled in the Amazonas region, Peru.

4. Discussions

Differentiating from previous studies of the suitability of the territory for the growing coffee [15,20–23,29,30,55,92], this study included a greater number of sub-criteria. Furthermore, only three [21,29,92] of the previous studies integrated AHP to rank and weigh the importance of the sub-criteria. In studies of the suitability of the territory for coffee growing, other crops [24–26] or agriculture in general [13,62,63], it is common to consider groups of climatological, edaphological, physiographic and socioeconomic criteria. However, this study included one group of criteria, that is, the most incidental disease and pest restrictions for coffee. These restrictions allow greater precision in determining the territory highly suitable for growing coffee in Amazonas region. It should be noted that the criteria used in the analysis of the suitability of the territory depend on the focus of the research and the availability of spatial data. For example, future studies may include cost–benefit, productivity, crop rate of return, costs of the land use changes, population benefited by the crop, or other economic sub-criteria [93]. However, the main problem lies in the lack of spatial data for the sub-criteria. In Peru, specifically in the Amazonas region, computer resources are scarce, even more so when it comes to specific studies of biological, environmental and social criteria at detailed local scales [94].

In terms of the development of coffee growing in Amazonas, our study shows that socio-economic (28.35%) and climatological (28.31%) criteria play a major role in coffee growing, followed by edaphological (25.03%) and physiographic (18.31%) criteria. However, for Mighty [21] and y Rono and Mundia [29], climatological criteria are the most important, followed by edaphological, socioeconomic and physiographic criteria. In contrast, although Ochoa et al. [92] they did not analyse socioeconomic criteria, in their study, the edaphological criteria are the most important, followed by the physiographic and climatological criteria. In fact, the number and the different sub-criteria used by each group of criteria, the local reality and the experience of the experts, contributed to differentiating the importance of the criteria. Of course, in our study, the slightly greater importance of the socio-economic criteria over the climatological and edaphological criteria concerning Amazonas may be due to the conservationist approach of the experts. Indeed, of the socio-economic sub-criteria, foremost were LULC (32.72%) and PNA (25.12%). Therefore, both are important here, as agriculture (mainly coffee and cocoa) and livestock farming have driven the greatest changes in LULC, making the region one of the most affected by deforestation [80,95]. In this context, public and private PNAs have been the main strategy for in situ conservation, highlighting that Amazonas is also one of the regions to record the highest number of PNAs [83].

In relation to climatological sub-criteria, the average annual temperature (22.37%) is the highest, followed by rainfall (21.4%); in a similar way, for Mighty [21] and Rono and Mundia [29], the temperature is the most important climatological sub-criterion; for their part, Ochoa et al. [92] state that precipitation is the most important. In fact, coffee crops are highly sensitive to climate, especially to the temperature at which they are grown [96,97]. Additionally, in this type of study, the suitability models are generated under current environmental conditions and must be constantly updated, since climate change is a factor that influences the patterns of climatological sub-criteria [15]. This is important for the agricultural sector in Latin America and the Caribbean because it is one of the most affected by climate change [7].

With regard to the edaphological sub-criteria, Akinci et al. [13] identified soil type as the most decisive factor for agriculture in general, and stoniness and drainage as the least important. Similarly, in our study (coffee growing), for edaphological sub-criteria, soil pH (29.22%) is indeed the most important, being followed by texture (19.06%); this also agrees with Ochoa et al. [92]. Conversely, for Rono and Mundia [29], soil pH is the least important. In fact, soil pH is key for the assimilation of nutrients by the plant, due to the fact that the availability of nutrients varies according to the levels of acidity; more importantly, in very high acidity, some minerals turn out to be toxic for the plants [51].

According to Rono and Mundia [29], elevation is the most important of the physiographic sub-criteria; conversely, Ochoa et al. [92] consider slope to be the most important; however, Mighty [21] consider that there is no significant difference (0.10%) between elevation and slope. In our study, of course, elevation was the most important (53.06%), followed by slope (24.18%) and aspect (22.75%). In addition, like Lara et al. [20], we integrated the aspect of the terrain as a physiographic sub-criterion, because to the fact that the aspect influences sunlight reception and temperature variations at the microclimate level [61]. In two locations in Costa Rica, Avelino et al. [98] found that crops on the easterly-facing slopes produced better quality coffee. The experts, therefore, highlighted the elevation from the point of view of coffee quality, because Duicela et al. [99], determined that the coffee varieties grown at higher elevation present higher organoleptic quality. This altitudinal factor has also contributed to the migration of coffee plantations to higher lands, and consequently more deforestation in the main coffee provinces of the region [80].

Regarding the socio-economic criteria, the distance to roads (21.94%) and distance to the water network (20.22%) have no significant difference (0.43%) for this study, closely related to the findings presented by Mighty [21] (1.40%). Definitely, in our study, the coffee experts prioritize the proximity to a road rather than a water body, in view of the fact that Amazonas has a privileged location in terms of water resources, while it lacks good road access and transportation for the arrival of inputs and the output of the product to the markets.

In the Amazonas region, the area modeled as "excellent" (912.48 km^2) for coffee cultivation is 113.5% greater than the area reported in the last national agricultural census of 2012 (427.44 km^2 [34]). Although the areas modeled as "excellent" for coffee cultivation are in line with the reference spatial distribution for validation (coffee areas in the ZEE [31] and geo-referenced farms), there are large "excellent" areas not considered in the ZEE and there are also some georeferenced farms that are not located in "excellent" areas. This is due to the fact that the ZEE is an old reference map (2010) and to the lack of a national (or regional) map of the current distribution of coffee. Additionally, Lara et al. [20] indicate that some validation plantations may be located in less suitable areas as agricultural practices such as planting shade trees improve the suitability of the land when temperatures drop, but coffee plantations should not be located in completely unsuitable areas.

Suitability maps for coffee diseases and pests showed that some areas of Condorcanqui, Bagua, Utcubamba, Luya and Rodriguez de Mendoza have ideal development conditions for coffee leaf rust, coffee berry borer and berry blotch. These provinces (except Condorcanqui) match those reported by the National Agrarian Health Service (SENASA), where they are constantly evaluating and applying control measures for these diseases and pests [40]. Due to this coincidence with SENASA, our temperature-based analysis is reliable. Unfortunately, diseases and pests depend largely on other factors such as relative humidity, photoperiod, elevation, percentage of shade, etc. [65–68]. Therefore, in future research it is recommended to consider all factors in order to improve the precision in the evaluation of land suitability. Additionally, we suggest using thematic layers with better spatial resolution, given that diseases and pests depend on microclimates [100,101], not well represented in layers with ~1 km resolution such as those in WorldClim.

The methodology used in this research is based on the integration of AHP, GIS and RS in order to analyze land suitability for coffee growing; the same can be applied not only to other coffee-growing areas, but also to other crops that have nutritional, economic and environmental importance, adjusting them to their local reality. Furthermore, these approaches have been influential in the field because of land suitability analyses identifying areas in which a crop is suitably developed, thus contributing to not over-exploiting the soil resource and consequently to a sustainable agriculture practice.

5. Conclusions

For the development of coffee growing in Amazonas region, the most important criteria are socioeconomic and climatological, followed by edaphological and physiographic. The edaphological sub-model has the largest "optimal" area for coffee cultivation in Amazonas region, while the sub-model with the smallest "optimal" area is the climatological one. In Amazonas, 11.4% (4803.17 km^2), 87.9% (36,952.27 km^2) and 0.7% (295.47 km^2) of the territory presented suitability "optimal", "suboptimal" and "unsuitable" characteristics, respectively, for coffee growing. It was found that, 8.0% (966.92 km^2), 18.6% (2628.00 km^2) and 7.6% (1208.18) present "unsuitable", "suboptimal" and "optimal" territory, respectively, for the development of diseases and pests, is "optimal" for growing coffee. It is recommended to orient coffee growing in 912.48 km^2 of territory in Amazonas, which has "excellent" suitability for coffee.

The integrated use of AHP, GIS and RS allowed the proper identification of areas with potential for coffee cultivation in Amazonas region and aims to guide the proper management of the territory. In addition, a methodological framework of potential application is provided for crops of economic interest in the Andean Amazon areas.

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