http://doi.org/10.1590/1678-992X-2022-0214
ISSN 1678-992X
Scientia Agricola
Research article

Physio-edaphoclimatic factors show optimal soil suitability for three tropical crops in the Ecuadorian Amazon

Marco Omar Vizuete-Montero[1*], Hilter Farley Figueroa-Saavedra[2], Asterio Denis Barbaru-Grajales[3], Holger Alfredo Zapata-Mayorga[4], Héctor Ramiro Herrera-Ocaña[3], Wladimir Moya[5]

[1]Universidad de Antioquia/Facultad de Ciencias Agrarias, Calle 10 Sur, N° 50e-31 – 0601060 – Medellín – Colombia.
[2]Escuela Superior Politécnica de Chimborazo/Facultad de Agronomía, Panamericana Sur km 1 ½ – EC060155 – Riobamba – Ecuador.
[3]Escuela Superior Politécnica de Chimborazo/ Facultad de Zootecnia, Panamericana Sur km 1 ½ – EC060155 – Riobamba – Ecuador.
[4]Universidad de las Fuerzas Armadas (ESPE) – Departamento de Ciencias Exactas, Av. General Rumiñahui s/n – 171103 – Sangolquí – Ecuador.
[5]Universidad de Los Lagos – Departamento de Ciencias Biológicas y Biodiversidad – Laboratorio de Ecología, Lord Cochrane 1046 – 5290000 – Osorno – Chile.
*Corresponding author <movizuetem@libertadores.edu.co>

Edited by: Quirijn de Jong van Lier

Received November 07, 2022
Accepted May 12, 2023

ABSTRACT: Favorable soil conditions are essential to the proper growth and production of any crop worldwide. Only 9 % of the Ecuadorian Amazon Region (EAR) territory is suitable for agriculture and/or livestock farming, due to limitations imposed by physio-edaphoclimatic factors. This study evaluated the soil potential suitability for coffee, cocoa and tropical pastures to determine optimal, moderate and marginal areas in three provinces in the EAR (Orellana, Sucumbios and Pastaza) under different agroecological conditions. On-site field work was carried out to analyze the soil profile to determine the mineral composition. Eight environmental variables were evaluated through the integration of GIS-based modeling to determine the agroecological zoning of the crops. The results showed that the main determining factors for optimal areas of soil suitability within the three provinces included soil depth (30 cm), organic matter content (5.3 %), concentration of macronutrients (2,700 mg kg^{-1}), and slope (< 10 %), whereas annual temperature (18-26 °C), annual precipitation (1200-3000 mm), altitude (0-500 m), and pH (4.38) were included for moderate and marginal areas. Depending on the crop and the province, soil suitability was classified into two or three classes (optimal, moderate, and marginal areas), relying on the agroecological conditions specific to each crop. This study highlights that all crops showed mostly optimal soil suitability for proper development under the agroecological conditions analyzed, which contributes to the provision of valuable information to decision-makers about key limiting factors, land-use planning and mapping soil suitability when considering the best location for a specific crop.

Keywords: GIS-based modeling, agroecological zoning, environmental factors, agricultural management

Introduction

In tropical and Amazonian regions, there is evidence that the introduction of agroforestry practices on cropland or pastureland can provide significant benefits in terms of ecosystem services (Veldkamp et al., 2020). In those ecosystems, economically important cash crops, including cocoa, coffee, and tropical pastures, are commonly associated with reductions in climate change impacts and to maintain ecosystem services (Garrett et al., 2021).

Ecuador is the leader in the production of fine aroma cocoa, with a 62 % share of the world market, supporting around 100,000 families (Díaz-Valderrama et al., 2020). In 2016, Ecuador produced around 253,000 metric tons of cocoa, where 70 % of the total production was considered as fine and aroma cocoa, which is exported primarily to the European market (Villacis et al., 2022). Furthermore, Ecuador has great capacity as a coffee producer, becoming one of the few countries in the world that exports all types of coffee: washed Arabica, natural Arabica and Robusta (Santos and Boffo, 2021).

Due to the soil conditions in the Ecuadorian Amazon Region (EAR) only 9 % of its territory is suitable for agriculture and/or livestock farming (Huera-Lucero et al., 2020). For this reason, it is necessary to know and evaluate the potential agroecological suitability of coffee, cocoa, and pasture agroforestry systems in the EAR to improve decision-making regarding land use planning and rational occupation of land suitable for these crops. Studies suggest that most of the population depends directly on primary activities (agriculture and/or livestock), which in turn are dependent on the seasonality and stability of climatic variables (precipitation and temperature) (Arroyo-Rodríguez et al., 2017). The main purpose of this study was to perform an agroecological zoning (AEZ) by identifying the optimal, moderate, marginal, and unsuitable potential for three economically essential crops (coffee, cocoa, and tropical pastures) in three provinces of the EAR (Sucumbíos, Orellana, and Pastaza) through field work and modeling using Geographic Information Systems (GIS). Our primary hypothesis was that the soil conditions of the three provinces are optimal for the proper development of these crops due to their geographical location.

Materials and Methods

Crop description

Three crops (cocoa, coffee, and tropical pastures) were selected on account of their economic importance in continental Ecuador. Cocoa (*Theobroma cacao* L.) is currently the third largest agricultural export crop. Its annual production represents 7 % of Gross Domestic Product (GDP), and it is estimated that there are currently around 500,000 hectares planted on approximately 10,000 farms; most of these farms, with an average of five ha, belong to small producers (Nair, 2021). The greatest concentration of cocoa cultivation is found in the coastal provinces of Los Ríos, Guayas, Manabí, Esmeraldas and El Oro, in the foothills of the Western Cordillera of the Andes and the northeastern provinces of Ecuador (Sucumbíos, Orellana, Pastaza, Napo) (Saravia-Matus et al., 2020). In the provinces of Orellana and Sucumbíos, it was estimated that the area planted has increased by approximately 20.000 ha of Nacional cocoa, making this area, during two to three years, one of the leading suppliers of cocoa for export (Middendorp et al., 2020).

Robusta coffee (*Coffea canephora* L.) is grown in Ecuador, mainly in the Amazon and coastal regions. It is one of the main crops in the country, involving some 50,000 families, most of them small producers that use agroforestry production systems (Viteri-Salazar et al., 2018). In Ecuador, this crop is characterized by its excellent yields in the field (on average 1000 kg ha^{-1}). Its ecological importance lies in the vast diversity of soils it is grown, mainly in rich agroforestry systems that contribute significantly to the conservation of phylogenetic resources, carbon sequestration and water balance. Due to Ecuador's privileged agro-ecological advantages, its planting and development have been facilitated in almost all its territory (Viteri-Salazar et al., 2018).

The tropical pastures of the Amazon region of Ecuador are important to the economic development of the country, due to their productive potential. The possibility of integrating the Ecuadorian Amazon into the national socio-economic system, and above all, the potential for agricultural improvement that it presents, demands increases in the forage production of existing pastures, as well as increases in the number of new pasture areas (Bedaso et al., 2022). Among the tropical pastures present in the Amazon and specifically in the provinces of Sucumbíos, Orellana and Pastaza are different species of grasses of the genus *Brachiaria* and legumes of the genus *Centrosema, Desmodium, Styloshantes, Arachis* (Motta-Delgado et al., 2019).

Study sites

The province of Sucumbíos is in the northeast of Ecuador at coordinates (00°06′00″ N, 76°52′01″ W), with an area of 18,084 km^2 and at an altitude between 405 and 2027 m. Its relief is mountainous, with a humid tropical climate and temperatures of up to 28 °C. Its main economic activities are agriculture, livestock and petroleum commercialization (Viteri-Salazar and Toledo, 2020). Orellana is located in the northeast of Ecuador (00°27′42″ S, 76°59′35″ W), with an area of 20,733 km^2 at an altitude between 255 and 3732 m. Its temperature varies between 20 to 40 °C, with a humid tropical climate. Its most important productive activities are agriculture, livestock, oil exploitation and timber (Viteri-Salazar and Toledo, 2020).

Pastaza is the largest province of Ecuador and the richest in biodiversity, located at coordinates (1°45′00″ S, 76°55′01″ W), with an area of 29,520 km^2 and at an altitude of 930 m. Ninety-five percent of the provincial flora is tropical rainforest, due to the annual rainfall that varies between 2000 and 4000 mm, favoring the formation of extensive and excellent pastures which are suitable for the raising of cattle. The climate is very humid and tropical, with an average temperature of 25 °C, and rainfall throughout the year. The main activities in this province are oil, timber, minerals, livestock, and agriculture (Viteri-Salazar and Toledo, 2020).

Conceptual model

A conceptual model that summarizes the steps that were carried out to determine the AEZ in the three provinces of the EAR is described in Figure 1.

Onsite work

Through field work, sampling units were established to consider the soil texture, topography, vegetation, and

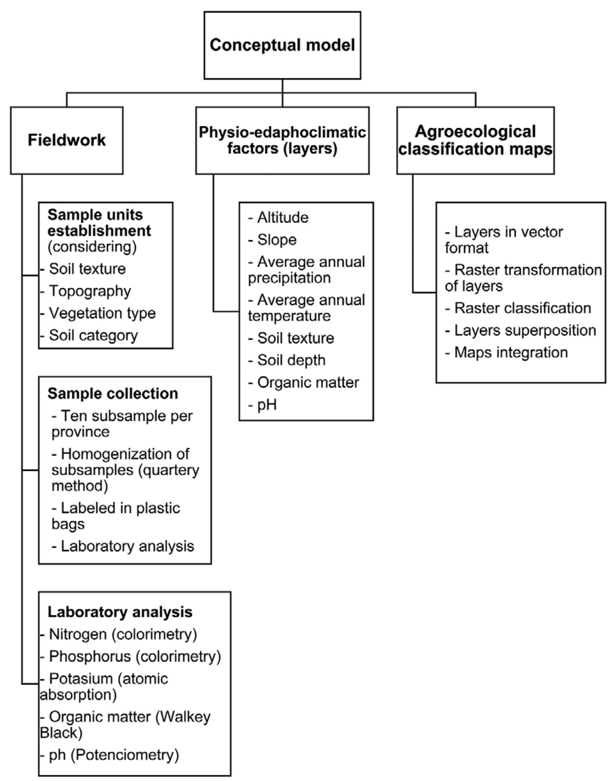

Figure 1 – Flowchart of the study.

soil category. Ten sub-samples of 0.05 kg were obtained for each province by zigzagging through the plots, obtaining a composite sample of 0.5 kg. The entire sample was homogenized using the quartering method and 0.05 kg of soil was extracted. It was placed in a plastic bag, labeled, and taken to the Instituto Nacional de Investigaciones Agropecuarias (INIAP) laboratories for subsequent analysis. An experimental design of completely randomized blocks was used where the significance level was calculated. Finally, the nitrogen (N), phosphorus (P), and potassium (K) elements, as well as Organic Matter Content (OMC), and pH contents were interpreted. N and P were determined by colorimetry methodology, K by atomic absorption, OMC by Walkey Black and pH by potentiometry. The first four parameters were expressed in kg ha^{-1}.

Physio-edaphoclimatic variables

According to the agroecological requirements of the cocoa, coffee, and tropical pasture crops, eight physical-geographical variables were selected: altitude, slope, average annual precipitation, average annual temperature, pH, soil texture, soil depth, and OMC.

The meteorological data on temperature and precipitation were provided by the Instituto Nacional de Meteorología e Hidrología (INAMHI) of Ecuador, from 13 meteorological stations, of which three meteorological stations were used with an average radius of action of 150 km, corresponding to the values reported in the literature for the collection of meteorological data suggesting 100 to 150 km of separation between stations. These stations had a direct meteorological impact in the study area covering a history of the period of 1990-2016.

Analyzing the available data, the isohyet method was applied, which provided a discontinuous rainfall distribution over the entire EAR, specifically in the provinces of Sucumbíos, Orellana and Pastaza. The mean annual temperature data were processed from the average of the mean temperatures recorded in each month of 2021. Precipitation data were processed from the precipitation calculation according to

$$P = \frac{\sum_i^n a_i * D_i}{A}$$

where: P is the precipitation of the study area (mm); Σ_i^n the summation of each isohyet (mm); a the area between each two isohyets (km^2); D the average precipitation between two isohyets (mm); i the isohyet (mm) and A the area of each study area (km^2)

Based on the above equation, the value of precipitation in each station was weighted according to each study area. All edaphic-physical-climatic variables were processed on a map scale of 1:2500 in ArcGIS software, transforming them from vector to raster format to facilitate processing and analysis. A digital elevation model (DEM) with an equidistance of 20 m was used for the relief varible.

Agroecological potential classification

To determine the AEZ of the three crops, the concept of agroecological potential was used as a starting point, which is understood as the set of quantitative and qualitative properties of the natural supply of the region, favorable for the adequate development of some crops (Lehmann et al., 2020). For this study, four types of agroecological potential were considered classified into four classes (optimal, moderate, marginal, and unsuitable). According to the Ministerio de Agricultura y Ganadería of Ecuador (MAGAP) and the INIAP, the optimal agroecological conditions from a physio-edaphoclimatic point of view for the three crops are described in Table 1.

Data processing

For the processing of the cartographic information of the different soil-physical-climatic variables and the zoning of the cocoa, coffee and tropical pasture crops, ArcGIS software version 10.3 was used, where they were first imported in vector format and then transformed into raster format for all the variables to obtain a better analysis and interpretation. The outputs of each variable in raster format were classified into four classes (optimal, moderate, marginal, unsuitable) according to the optimal requirements for each crop using the "reclassify tool" to reclassify variables separately.

Once the reclassification had been done, a superimposition of layers was applied using the *weighted overlay* tool, to obtain a final map integrating all the variables, considering the weighting and the relative importance of each variable, which differ according to

Table 1 – Optimal agroecological conditions for cocoa, coffee, and tropical pastures.

Crop	Altitude	Slope	Temperature	Precipitation	Soil texture
	m asl	%	°C	mm	
Coffee	400 - 1800	0 - 25	17 - 23[a]	800 - 2000[a]	Loam; clay loam
			20 - 26[b]	2000 - 3000[b]	
Cocoa	0 - 500	0 - 25	18 - 26	1200 - 3000	Loam; clay loam, silty loam
Tropical pastures	0 - 1200	0 - 25	18 - 32	800 - 3500	Loam soils with high organic matter content

[a]Arabica coffee variety; [b]Robusta coffee variety.

the crop. For example, more importance was given to the soil texture, with a weighting of 45 % for adequate development of the coffee crop, compared to other variables such as elevation (15 %), or precipitation (5 %). For cocoa cultivation, greater importance was given to soil texture (40 %) and slope (35 %), compared to elevation (5 %) or temperature (10 %).

Results

Onsite work

The optimum soil potential zones were found in areas with slopes no greater than 10 %, mainly those at the foothills of the primary and secondary forests of the three provinces, where dominant soils were rich in macro-nutrients such as N, P, K, with an average concentration of 2,700 mg kg^{-1} of soil. Meanwhile, Mg showed a 118.8 mg kg^{-1} concentration, Ca (48 mg kg^{-1}), and Zn (3.48 mg kg^{-1}). The soils were of loamy texture with high OMC (5.3%), a pH level of 4.38, and an average depth of 30 cm of arable land.

Cocoa agroecological zoning

The AEZ for cocoa in the three provinces showed optimal and moderate suitability zones (Figure 2). Optimal zones were found in most of the territory of the provinces of Sucumbíos, Orellana, and Pastaza, with patches of moderate agroecological suitability in the western part of the three provinces. Optimal zones covered 1,601,907 ha, 2,133,315 ha, and 2,924,274 ha, for Sucumbíos, Orellana, and Pastaza, respectively, while moderate zones represented 125,180 ha, and 28,548 ha, for Sucumbíos, and Orellana, respectively (Table 2). The modeling results did not identify marginal or unsuitable areas for cocoa cultivation in any of the provinces.

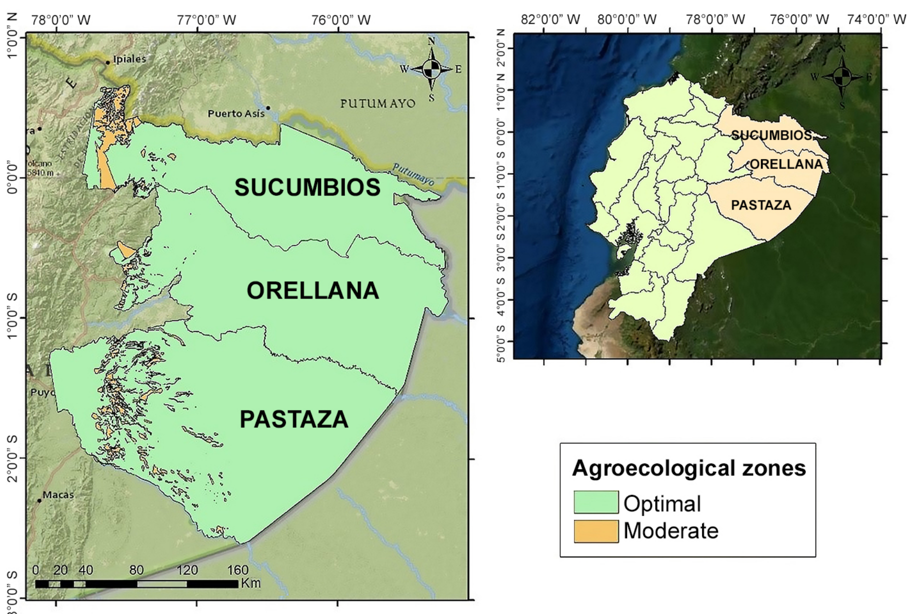

Figure 2 – Agroecological zoning for cocoa cultivation within the three provinces of the Ecuadorian Region Amazon.

Table 2 – Area of optimal, moderate, and marginal soil suitability for cocoa, coffee, and pasture crops in the three provinces of the Ecuadorian Region Amazon.

Province	Crop	Optimal	Moderate	Marginal
		ha		
Sucumbios	Coffee	726,571	889,075	111,355
	Cocoa	1,601,907	125,180	-
	Tropical pastures	1,377,907	349,116	-
Orellana	Coffee	1,269,090	878,419	14,274
	Cocoa	2,133,315	28,548	-
	Tropical pastures	1,765,902	143,159	-
Pastaza	Coffee	1,471,313	2,437,201	447,220
	Cocoa	2,924,274	-	-
	Tropical pastures	2,747,414	176,835	-

Blank spaces represent the absence of moderate and marginal areas for the three crops.

Coffee agroecological zoning

The AEZ for coffee in the three provinces showed optimal, moderate, and marginal suitability areas (Figure 3). Optimal zones were found mostly in the eastern part of the EAR, moderate zones in the central part, and marginal zones in the northwest and southwest of the region. Optimal zones covered an area of 726,571 ha, 1,269,090 ha, and 1,471,313 ha, moderate zones 889,075 ha, 878,419 ha, and 2,437,201 ha. In contrast, marginal areas were 111,355 ha, 14,274 ha, and 447,220 ha, for the provinces of Sucumbíos, Orellana, and Pastaza, respectively. The modeling results did not determine areas unsuitable for the development of coffee cultivation in any province (Table 2).

Tropical pastures agroecological zoning

According to the in situ and ex situ field phase of tropical pastures in the EAR, the soil pH showed an average of 6.4, with 8 to 12 earthworms per m^2. A minimal incidence of spittlebugs was observed, mainly in the areas suitable for pasture cultivation. The physical-geographical potentials for planting and development of tropical pastures showed optimal potentials of 1,377,907 ha, 1,765,902 ha, and 2,747,414 ha, and moderate potentials of 349,116 ha, 143,159 ha, and 176,835 ha, for the provinces of Sucumbíos, Orellana, and Pastaza, respectively. The modeling results did not determine marginal zones or zones unsuitable for developing tropical pastures (Table 2).

The AEZ for tropical pastures showed both optimal and moderate agroecological suitability zones. The optimal zones were found throughout the territory of the three provinces while the moderate zones were distributed in patches in the western and southern part of Pastaza province, central-eastern part of Orellana, and throughout the territory of Sucumbíos (Figure 4).

Discussion

The suggested optimal agroecological requirements for cocoa cultivation and its identification in the area are altitudes between 0 and 500 m, slopes between 0 and 25 %, temperatures between 18 and 26 °C, average rainfall between 1200 and 3000 mm per year with a loamy-clayey-loamy soil texture (CATIE, 2015). Based on these model conditions, the AEZ for cocoa in the three provinces showed, in general, optimal and moderate suitability zones. The processing and spatial representation of cocoa agroecological zoning made it possible to evaluate the optimal zones for cocoa cultivation based on the variables of altitude, average annual precipitation and temperature, slope, and soil texture. In the state of Tabasco, Mexico, optimal (174,000 ha) and moderate (31,000 ha) areas have been determined to be smaller than in the EAR due to the size of the study area (Ramírez-Jaramillo et al., 2021). However, they highlighted factors such as temperature and soil texture as the determinants that can adequately identify optimal and moderate zones for cocoa cultivation. In addition, it has been found that climatological criteria, such as annual temperature and precipitation in the coldest quarter, are the factors that most influence the optimal zones (Rojas-Briceño et al., 2022). In concordance with the present study, edaphoclimatic factors such as soil texture, slope, and average annual precipitation were determinant in modeling the optimal and moderate zones' temperatures.

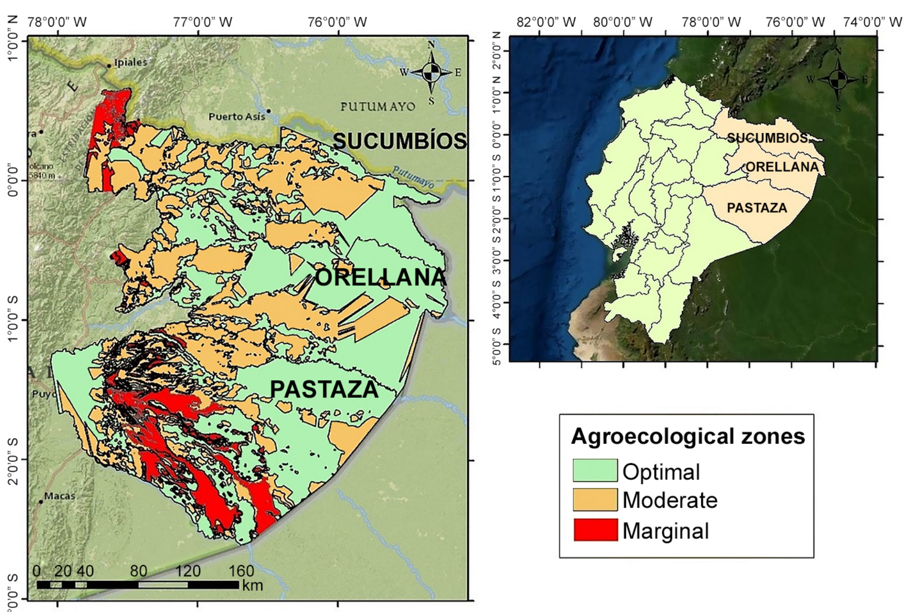

Figure 3 – Agroecological zoning for coffee cultivation within the three provinces of the Ecuadorian Region Amazon.

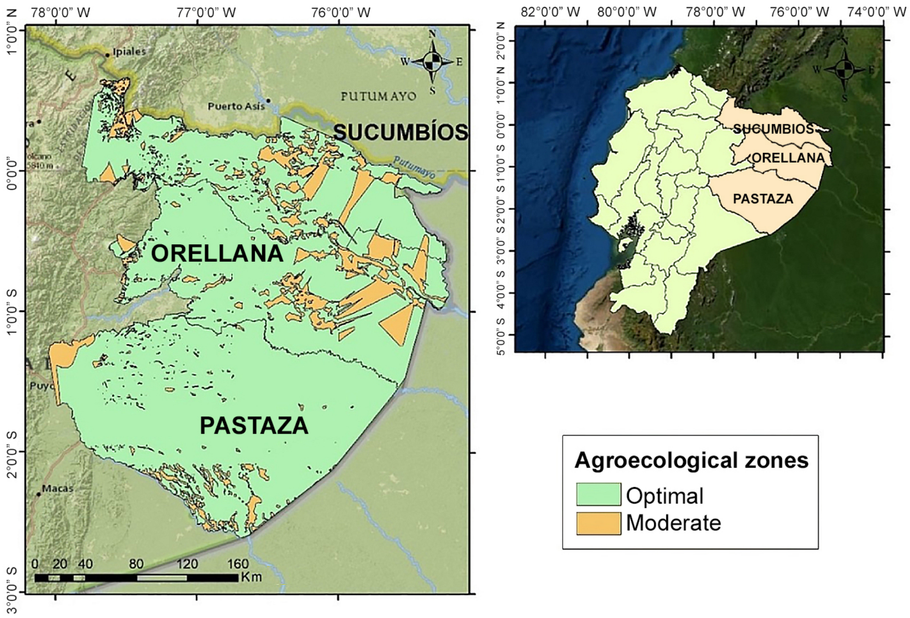

Figure 4 – Agroecological zoning for pastures cultivation within the three provinces of the Ecuadorian Region Amazon.

On the other hand, the suggested optimal agroecological requirements for coffee cultivation are an altitude between 400 and 1800 m for Arabica coffee and between 0 and 600 m for Robusta, slopes between 0 and 25 %, temperatures from 17 to 23 °C, (Arabica) and from 20 to 26 °C (Robusta), average rainfall per year between 800 mm (Arabica) and 2000 mm (Robusta), with a loam-clay-loam soil texture (CATIE, 2015). Based on these model conditions, the AEZ for coffee in the three provinces showed optimal, moderate, and marginal suitability areas.

Based on GIS modeling, optimal zones of coffee were found on slopes between 0 and 25 % with temperatures from 17 to 26 °C, rainfall regime 800 to 2000 mm, and at an altitude between 400 and 1800 m. These results align with those recorded by González and Santana (2016) in which optimal zones were found in semi-warm climates (18 to 22 °C) with 1500 to 2000 mm and at an altitude between 1100 and 1500 m. It has been found that minimum temperatures were insignificant in determining optimal zones, as low temperature is determined by lower tolerance to cold temperatures in coffee (Pérez-Portilla and Geissert-Kientz, 2006). However, other factors such as drainage, slope, and soil texture had an influence. In the present study, soil texture and slope were more determinant in identifying optimal areas compared to other environmental factors.

Regarding cocoa and tropical pastures, the provinces of Pastaza and Sucumbíos showed optimal potential for most areas, and moderate potential for the minor parts. These results corroborate those reported by MAGAP, since the land in both provinces has a sandy-loamy texture, with slopes between 25 and 50 %, moderately deep, with little stoniness and moderate drainage, ideal for the cultivation of cocoa and tropical pastures. Certain areas of marginal suitability in the province of Orellana limit the development of coffee cultivation, mainly because they have slopes greater than 70 %, with shallow depth and abundant stoniness. In addition, it has a shallow water table with a very low pH.

Based on the economic AEZ of Ecuador, reported by MAGAP, the provinces of Sucumbíos and Orellana have high (or optimum) agroecological potential. This is caused by the fact that the soils in the province of Sucumbíos have a loamy-sandy-loam texture, with slopes between 25 and 50 %, moderately deep, with little stoniness and moderate drainage, again ideal for the development of coffee and cocoa. In the province of Orellana, where optimal, moderate and marginal potential for coffee cultivation was presented, this may be due to the geographical conditions of the province, given its gentle and moderate slopes (1-18 %), with rainfall between 1500 and 2000 mm, in semi-warm zones with a thermal range from 18 °C to 22 °C (González and Santana, 2016). Results of other studies mention that the optimal natural environment for coffee cultivation is in the low mountain areas, between 1100 to 1500 m asl. These conditions are similar to those found in the provinces of Orellana, given that the ambient temperature is between 16 to 24 °C, with a rainfall of 800 to 2000 mm, and an altitude between 1800 and 2000 m asl. This is because climate conditions tend to be semi-warm and humid, and the soil has a moderate to steep slope, restricting crop implantation (Santana et al., 2021).

In the mountains of Ruanda, coffee is grown on steep slopes of up to 55 %. Approximately 21 %

of the country has medium yield potential, ranging from 1.0 to 1.6 tons of coffee ha^{-1}, and 70 % has low yield potential (< 1000 kg coffee ha^{-1}). Only 9 % of the country has a high yield potential, ranging between 1.6 and 2.4 tons of coffee ha^{-1} (Nzeyimana et al., 2014). It emerges that there is a significant spatial variation in potential productivity indicators. Therefore, there is considerable potential for increasing the coffee production area and productivity in lands such as the EAR. Coffee has high potential for cultivation in areas of very humid premontane forests under zonal conditions (without limitations), as is the case for the EAR or in the presence of deciduous forests. Moist forests in premontane zones may also have high potential, although this was not reflected due to technical problems with the bio-temperature formula (González et al., 2022).

The extension of pasture areas has been increasing significantly in the Amazon region over the last few years. It is noteworthy that due to population growth, the natural forests of the EAR have been transformed into large pastures for cattle ranching to meet food demands. This increase in pasture areas is associated with deforestation, cattle trampling, land compaction, and contamination of water sources, which is reflected in a loss of biodiversity and an increase in the effects of climate change. The need to continuously apply appropriate management practices that integrate an agro-silvo-pastoral system to reduce the effects of climate change is ongoing.

A preliminary evaluation carried out by Caicedo-Vargas et al. (2022), of agro-silvo-pastoral systems as an alternative for pasture management in the EAR demonstrated that the best combinations of pastures to increase biomass, reduce environmental impacts on livestock activity and improve the suitability of the agricultural soil are combinations of Mulato II + *Gliricidia sepium* + *Psidum guajava*; Mulato II + *Trichantera gigantea* + *P. guajava*; Mulatto II + *Flemingia macrophylla* + *P. guajava*; Mulatto II + *Leucaena leucocephala* + *P. guajava*; Mulatto II + *Erythrina* spp. + *P. guajava*.

It is recognized that when producing cocoa, coffee, or pasture fruits, significant quantities of nutrients are extracted from the soil. Service trees present in agroforestry or silvo-pastoral systems, through their contribution of leaf litter and recycling of nutrients, make it possible to achieve stable yields, even higher than those obtained under traditional management systems. Trees present in agroforestry systems generate ecosystem services that have enormous importance for humanity.

In many areas of the Ecuadorian Amazon, crops or pastures are grown on soils unsuitable for their development, mainly because they are not very fertile, are susceptible to erosion and nutrient loss, and are in areas with high rainfall (Pimentel, 2006). These drivers, together with the lack of appropriate production technologies and the low investment capacity of producers, have resulted in low productivity in agricultural production systems, soil degradation, and, in many cases, land abandonment (Zerssa et al., 2021). It is worth mentioning that when crops such as coffee, cocoa, or pastures are grown on forested soils, it is necessary to promote strategies based on forest-like production systems.

One of the strategies is to incorporate live fences with timber trees such as palo cruz (*Tabebuia nodosa* Griseb), chontaduro (*Bactris gasipaes* Kunth), jacaranda (*Jacaranda mimosifolia* D.Don), guabo (*Inga edulis* Mart), and peine de mono (*Apeiba membranacea* Spruce ex Benth), which are species that improve the physical-chemical and microbiological characteristics of the soil. These plant arrangements balance and improve soil drainage, contributing to the formation of several microclimates, important elements for the cattle not to suffer from thermal stress and to reduce the effects of climate change (Ngo Bieng et al., 2022). The best productive results were achieved by applying forage plant material, such as Flemingia, in the management and conditions applied in the EAR (Phelan et al., 2015).

The basic principle of the AEZ is to understand the multiplicity of agronomic, economic, and environmental criteria that determine the performance of an agroecosystem, and then determine the nature and extent of changes that need to be introduced to achieve greater productivity. Furthermore, livestock is an essential component of pastures and agriculture, although its role is less relevant than crop production. However, its contribution and interactions with crops are key to promoting sustainable agriculture and environmental protection (Basu et al., 2018).

The success of a sustainable agricultural management program is based on the best choice of crops adapted to specific soils under specific environmental conditions. There is a strong interaction between soil properties and crop needs. In certain cases where soil quality does not meet crop needs (soil suitability is defined as marginal or unsuitable), this can be reversed by improving soil management (Amelung et al., 2020). Therefore, improving farm management practices by fortifying soil physicochemical properties can help improve soil suitability for optimum production.

This study emphasizes that the current importance of using GIS-based modeling as a complementary tool for the study of land use is imperative to identify the potential and limited zones for crops growing in a study area from a perspective of rational exploitation of agroforestry systems. Modeling based on GIS has been applied to other organisms such as plants (Yan et al., 2020), animals (Akçay et al., 2020) and marine species (Moya et al., 2017) to determine areas of suitability for their establishments and distributions without altering the natural conditions of their environment. However, in agrosystems, the use of GIS/computer models and spatial analysis to determine land suitability is essential because of their important role in land planning.

It is essential to carry out adequate agroecological zoning through GIS technologies complemented with agro-silvo-pastoral management practices on farms to improve the dynamics of production systems in order to understand the interrelationships between environmental criteria with agronomic and economic factors. This enables the suggestion of changes in public policies to delimit conservation areas of natural forests in the Amazon while coexisting with agroforestry systems and avoiding the expansion of the agricultural frontier.

In conclusion, the main factors of influence on optimal areas of soil suitability within the three provinces include soil depth, organic matter content, proper concentrations of nutrients and minerals, and slope, whereas for moderate areas, they include annual temperature, annual precipitation, altitude, and pH. Depending on the crop as well as the study area, soil suitability can be classified into two or three classes (optimal, moderate, and marginal areas). Based on the initially stated hypothesis, all crops show optimal soil suitability for proper development under the analyzed agroecological conditions. The observed coffee-cocoa and pasture soil suitability under the environmental criteria can provide valuable information to decision-makers about key limiting factors.

Governments should improve legal, institutional, policy, and financial frameworks to enhance the value of agro-silvo-pastoril systems on private land and promote measures to protect national forests and protected areas, including investing in modern technologies to monitor land-use change in real time. For future research, we recommend integrating environmental, agronomic, and economic factors to determine the dynamics of land use and land cover, the dynamics of production systems, including cropping systems, as well as storage and market issues, to diagnose the situation in a given AEZ.

Authors' Contributions

Conceptualization: Vizuete-Montero O, Herrera-Ocaña H, Figueroa-Saavedra H, Zapata-Mayorga H, Barbaru-Grajales A, Moya W. **Data curation:** Vizuete-Montero O, Herrera-Ocaña H, Figueroa-Saavedra H. **Formal analysis:** Vizuete-Montero O, Herrera-Ocaña H, Figueroa-Saavedra H, Moya W. **Investigation:** Vizuete-Montero O, Herrera-Ocaña H, Figueroa-Saavedra H, Zapata-Mayorga H, Barbaru-Grajales A. **Methodology:** Herrera-Ocaña H, Figueroa-Saavedra H, Zapata-Mayorga H, Barbaru-Grajales A. **Project administration:** Vizuete-Montero O, Moya W. **Supervision:** Vizuete-Montero O, Moya W. **Writing-original draft:** Vizuete-Montero O, Herrera-Ocaña H, Figueroa-Saavedra H, Zapata-Mayorga H, Barbaru-Grajales A. **Writing-review & editing:** Barbaru-Grajales A, Moya W.

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