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Factors influencing avocado and coffee production in Huatusco, Veracruz

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Abstract

Avocado and coffee production sustain the agricultural economy of Huatusco, Veracruz; however, it faces significant challenges such as coffee leaf rust and other pathogens. Therefore, the objective of this research is to develop a biophysical and descriptive characterization to analyze the environmental conditions, agricultural practices, and socioeconomic factors influencing the production of both crops. This approach will enable the development of strategies to optimize production, promote sustainability, and strengthen the resilience of local producers. The methodology consisted of a biophysical characterization based on cartographic analysis, complemented by a descriptive characterization using both local and technical knowledge related to crop management, challenges faced, and actions taken to mitigate impacts. The results indicate that shaded coffee production accounts for 69% of the agricultural land, while avocado covers 28 %. Avocado production shows good development, although it is affected by pathogens and market fluctuations. The coffee sector continues to struggle with persistent issues such as coffee leaf rust and a shortage of labor, which has led to increased production costs. Based on these findings, the implementation of specific management strategies is recommended: for avocado, improving soil management and the adoption of drip irrigation systems are necessary; for coffee, the Colombia and Costa Rica varieties remain productive and rust-resistant, although drought has adversely affected the flowering stage. Enhanced soil and water management practices are needed, along with efforts to address labor shortages that are contributing to rising production costs.

Keywords: Agricultural practices, irrigation, phytosanitary control, *Persea americana* var. Hass, *Coffea arabica* var. Colombia and Costa Rica.

Introduction

The biophysical and descriptive characterization of crops is an important aspect for understanding and optimizing agricultural practices, especially in regions with diverse crop systems such as the central micro-watershed of Huatusco, Veracruz. Biophysical characterization involves the analysis of physical factors such as soil, climate, topography, and water availability (Nkiaka et al., 2024). Evaluating the biophysical aspects of agricultural systems through their physiographic and climatic characteristics provides communities with specific information that is useful for decision-making in production management (Ruiz-García et al., 2020). Descriptive characterization, on the other hand, involves the identification of crop varieties, the agricultural practices employed, and their adaptation to different climatic conditions, soil types, water requirements, pests, and diseases, as well as certain socioeconomic factors influencing production. This characterization is essential for informed decision-making related to the management and optimization of agricultural yields (Malagón & Prager, 2001).

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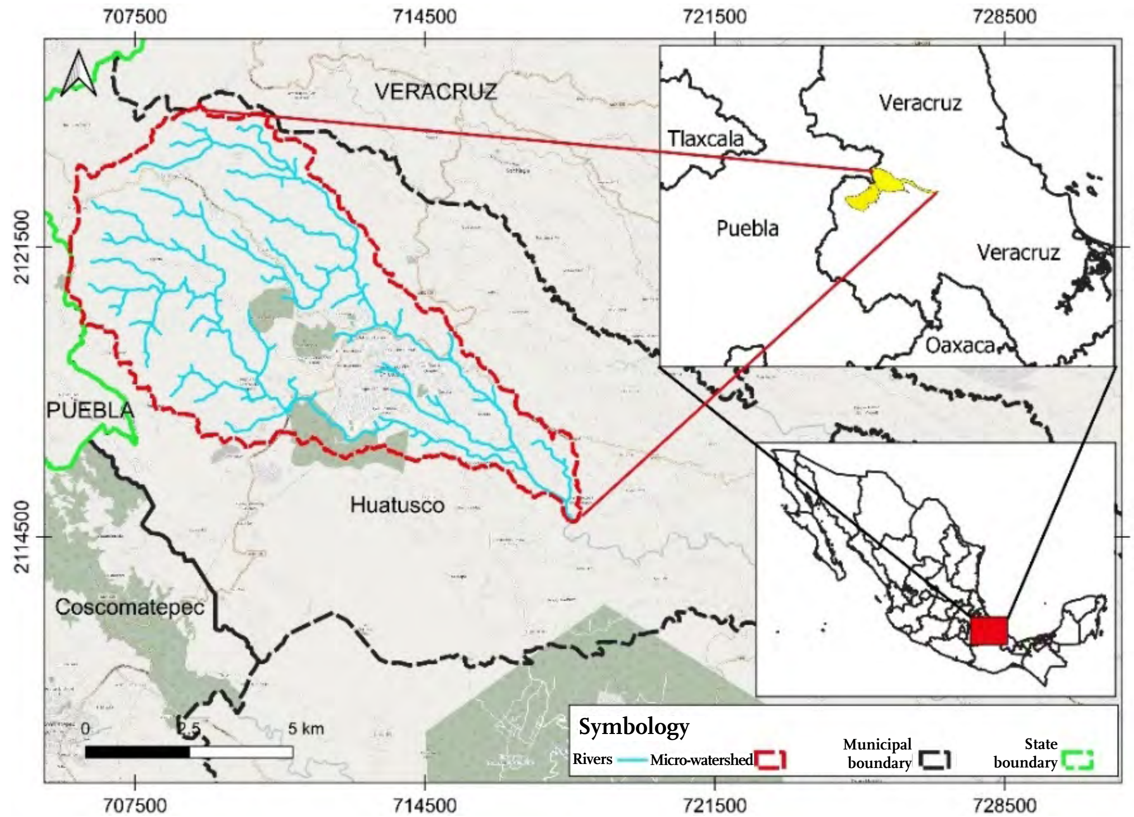
Figure 1. Geographic spaces of the study area.



Source: Compiled by the authors using information from INEGI and CONABIO.

In this context, the central micro-watershed of Huatusco shows optimal biophysical characteristics for the establishment of permanent agricultural systems: primarily shaded coffee (Sc) and avocado (Av), which are essentially the main pillars sustaining the local economy (García et al., 2023). However, the production of these crops is commonly affected by crop-specific pests and diseases, climatic variability, inadequate soil and water resource management, and the influence of market dynamics. These factors have a direct impact on the economic stability of producers (Ploetz, 2013; Bunn et al., 2015).

As previously mentioned, one of the most significant crops in this micro-watershed is coffee (*Coffea arabica*), as Mexico ranks 11th among global green coffee producers and 1st in organic coffee production (Centro de Estudios para el Desarrollo Sustentable y Soberanía Alimentaria, 2020). Approximately 80 % of national production is geared toward export, while the remaining 20 % is destined for the domestic market (Fideicomisos Instituidos en Relación con la Agricultura, 2019). This industry accounts for 0.66 % of the national agricultural GDP, with Veracruz contributing 24 % (Gobierno del Estado de Veracruz, 2019), making it a significant source of foreign exchange and employment (Martínez-López et al., 2022).

In addition to coffee, avocado cultivation (*Persea americana* var. Hass) has increased in the region, driven by a significant rise in international demand over the past decade. In response, Mexico has positioned itself as the global leader in avocado production and export, contributing 32 % of the total export value worldwide (García et al., 2023). Although the state of Veracruz accounts for only 0.29 % of national production (García et al., 2023), the establishment of this crop—particularly the Hass variety—has expanded notably over the past 20 years. This growth has had a positive impact on the regional economy by generating multiple sources of employment (DANE, 2016).

Considering the economic significance of these crops, it is essential to sustain their productivity and long-term viability. This underscores the need for in-depth knowledge of the factors influencing their establishment and performance. The aim of this characterization is to deliver a comprehensive overview of the biophysical conditions, management practices, existing challenges, and both corrective and preventive strategies that affect the development of coffee and avocado cultivation within the micro-watershed. The resulting information is intended to support decision-makers and producers in optimizing productivity, minimizing risks associated with climatic and soil-related factors, and ensuring the resilience and continuity of local agricultural systems.

Materials and Methods

Study area

The study area is the central micro-watershed of the municipality of Huatusco, Veracruz, located between parallel 19° 01' N and meridian 97° 03' W (Figure 1). This micro-watershed is part of the Jamapa river basin, which belongs to the Central Gulf Administrative Hydrological Region. The area has an average annual temperature of 17.5 °C and average annual precipitation of 1 750 mm. The micro-watershed was selected it presents a variety of biophysical conditions suitable for agricultural systems, specifically coffee and avocado, which allow us to find out which conditions are best for crop growth.

This research was conducted following these stages: i) review of official cartographic information and creation of reference maps; ii) field reconnaissance of the study area and establishment of control points to develop soil type, land use, and vegetation maps; iii) preparation of specific cartography for the study area based on field data; iv) biophysical characterization of the reference crops; and v) description of crop varieties, distribution, planting density, agricultural practices employed, and their adaptation to varying climatic conditions, soil types, water requirements, pests, and diseases, and socioeconomic factors influencing production.

Biophysical characterization

This characterization was conducted through the analysis of cartographic data related to the following biophysical aspects: climate, relief, slope, altitudinal range, soil type, and vegetation.

Data and information sources

Slope and altitudinal range data were obtained from the Continuo de Elevaciones Mexicano 3.0 (CEM 3.0) by INEGI (2023). To generate the soil type map, targeted sampling was carried out in agricultural production areas. Sample collection was supported by local knowledge from producers and the edaphological vector dataset at a scale of 1:250,000, Series II (INEGI, 2014). Land use and vegetation cartography was generated through supervised classification based on 2023 SENTINEL satellite images provided by the United States Geological Survey (USGS). Meanwhile, climatic data were extracted from the climate, precipitation, and average annual temperature layers provided by CONABIO.

Land use and vegetation mapping

A supervised classification was performed based on the preprocessing of SENTINEL satellite images, using the Semi-Automatic Classification Plugin (SCP) in QGIS (Congedo, 2021). A false-color band composite (bands 4, 3, and 2) was used to define six land cover classes: urban, temperate forest, shaded coffee, avocado, lemon, and grassland. This approach enabled the identification and quantification of surface areas, distribution, and the biophysical conditions in which the reference agricultural systems are established.

Soil type mapping

This map was developed based on data reported by INEGI and was supplemented with soil sampling conducted in agricultural areas. The sampling was carried out with the support of local knowledge, following the methodology proposed by Ortiz et al. (1990), which involves conducting field surveys with farmers to generate control points and establish the boundaries of different soil types. The sampling intensity depended on the frequency of crop cultivation in the study area. A total of 15 composite samples were collected throughout the micro-watershed and were distributed across the upper, middle, and lower sections of the plots.

Subsequently, laboratory analysis of the samples was conducted to determine the values and parameters of the following physical and chemical properties: color, texture, permanent wilting point (PWP), field capacity (FC), electrical conductivity (EC), porosity (P), pH, and bulk density (BD). Based on the report provided by INEGI, the laboratory data, and the methodology of Ortiz Solorio, a new taxonomic classification of the region's soils, was developed according to the World Reference Base for Soil Resources (FAO, 2014). Finally, the soil type map was produced using this updated taxonomic classification.

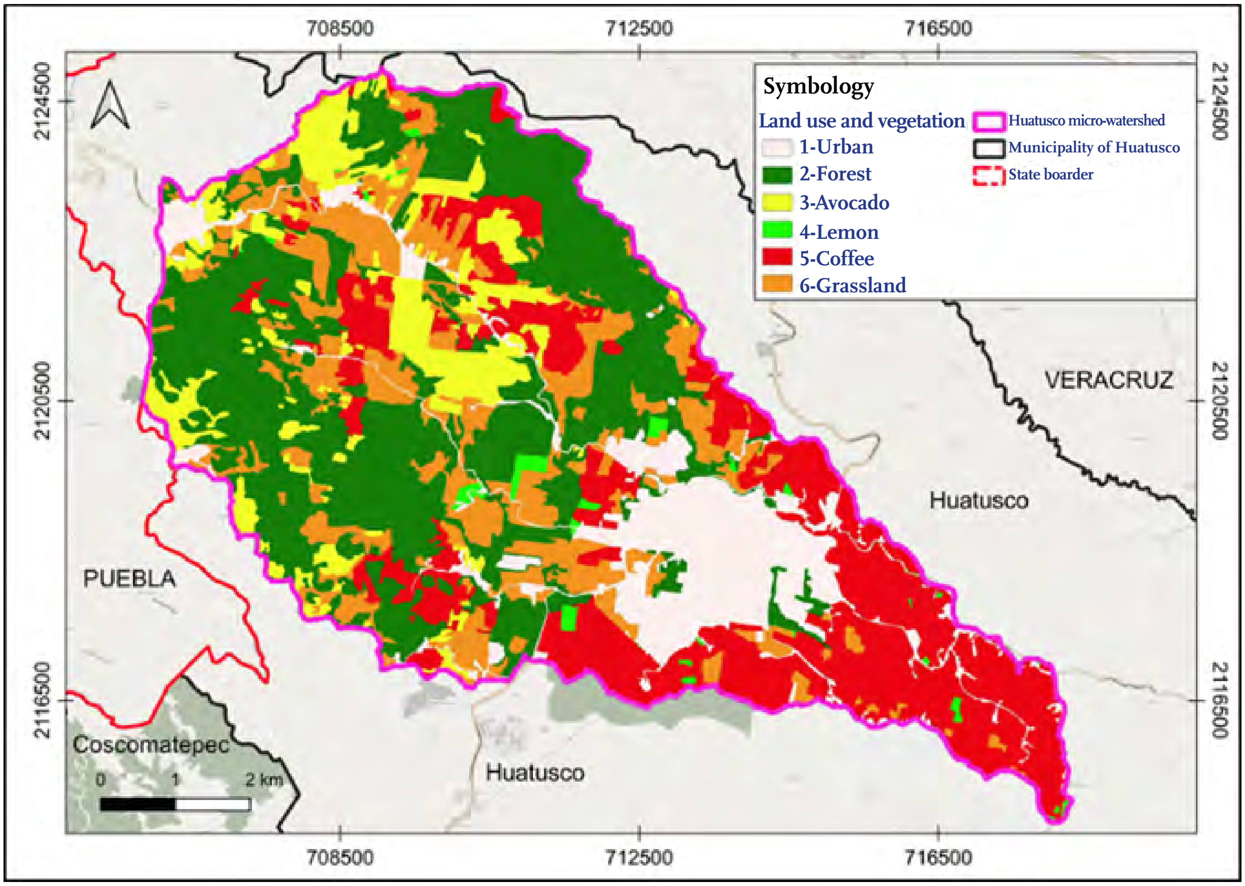
Slope and altitudinal range mapping

The slope and altitudinal range maps were generated by processing data from the CEM using the QGIS interface. The initial slope values were reclassified to produce a new classification expressed in percentage ranges: 0-2, 2-4, 4-8 and de 8-15 %. The altitudinal range was derived by generating a contour layer, which was used to define elevation intervals of 250 meters.

Characterization of agricultural crops

The description of the agricultural crops was developed through on-site participation with the producers. Field visits were carried out with 15 informants per crop, following the methodology of Ortiz-Solorio & Gutiérrez-Castorena (1999), which involves complementing local knowledge with technical expertise to provide a detailed characterization of the agricultural crops. The informants were selected for being members of the community with extensive knowledge of crop management, specifically coffee and avocado. The producers also contributed information to describe the activities required to achieve optimal

Figure 2. Distribution and area covered by the reference crops: avocado and coffee.



Source: Compiled by the authors.

production, the environmental and socioeconomic challenges they face, and the actions they take to mitigate these impacts.

Results and Discussion

Distribution and area covered by the reference crops

According to the supervised classification, the micro-watershed evaluated covers a total area of 5 939.5 hectares, where agricultural land use predominates with 35.4 % (2 104.3 ha), followed by temperate pine forest at 34.2 % (2 031.2 ha), and areas designated for livestock at 17.2 %.

Shade-grown coffee is the main crop in the agricultural area, covering 1 457 hectares (69.2 %) and mostly situated in the lower part of the micro-watershed. In contrast, avocado is the second most prominent crop, occupying 592.4 hectares (28.2 %) and primarily located in the upper part of the micro-watershed (Figure 2).

Influence of biophysical factors on coffee and avocado production

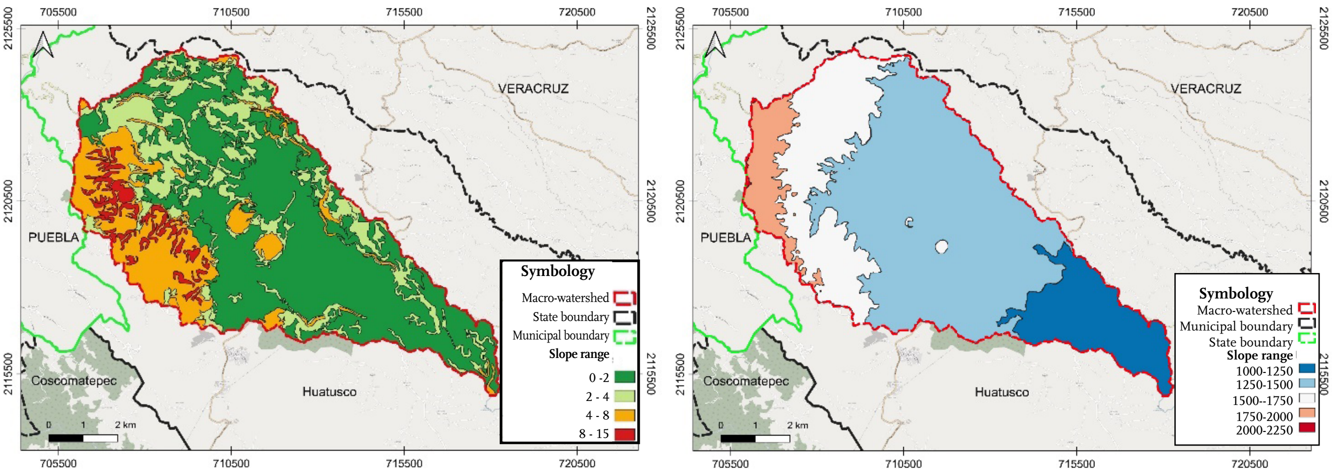
Climatic conditions

Within the micro-watershed, four distinct climates were identified according to García's classification (2024) (Table 1). The predominant climate is warm sub-humid, covering 48.7 % of the total area, followed by humid temperate at 20.9 %.

Avocado

According to different studies, the environmental factors that have the greatest impact during the development and production stages of avocado cultivation are temperature, wind, and precipitation (Campos et al., 2015). The optimal temperatures for this variety range between 5 and 17 °C (DANE, 2016), and it requires between 1 200-1 600 mm of well-distributed rainfall throughout the year (Bernal-Estrada et al., 2020). The characterization results indicate that 70.9 % of the crop has been established in a humid-temperate climate. It is also observed that 74.3 % is located within an average annual temperature range of 16-18 °C, while 87.7 % has been planted in areas receiving approximately 1 900 mm of precipitation. These climatic conditions are favorable for maintaining optimal crop yields, as avocado adapts well to humid and sub-humid climates (DANE, 2016). However, excessive rainfall can cause damage due to pathogens (Cruz et al., 2020). Intense rains prolong moisture on the foliage, increasing anthracnose infection during flowering and fruiting stages, which results in greater fruit drop and reduced economic yield (DANE, 2016). Temperatures outside the optimal range

Figure 3. Slope percentage (a) and elevation range (b) of the micro-watershed.



a) b)

Fuente: Elaboración propia, con información de INEGI (2013).
Source: Compiled by the authors using information from INEGI (2013).

can drastically reduce crop yields, especially when they coincide with the reproductive stage (DANE, 2016).

Coffee

According to different studies, temperature and precipitation significantly affect coffee yield (Gabriel-Hernández & Barradas, 2024). The optimal environmental conditions for the yield of *Coffea arabica* are as follows: ideal temperature of 18.7 °C, within a range of 17 to 21 °C; regarding precipitation, an average annual rainfall of 1 770 mm is required, with a range between 1 000 and 3 000 mm (Gabriel-Hernández & Barradas, 2024; Jiménez et al., 2023). The characterization results indicate that 77.2 % of the crop is established in a humid warm climate, 69.8 % of the crop is located in areas with an average temperature of 19 °C, and 85.4 % is planted in areas receiving around 1 900 mm of precipitation, ranges that fall within the ideal conditions to maintain good crop yields.

Slopes and Altitudinal Range

Table 1 shows the distribution of reclassified slopes. In the study area, slopes between 0-2 (59.2 %) and 2-4 (20.1 %)predominate (Figure 3a). The altitude range covering the largest area is 1 250-1 500 meters above sea level, with 55.8 %, followed by 1 500-1 750 meters above sea level with 22.2 % (Figure 3b).

Avocado

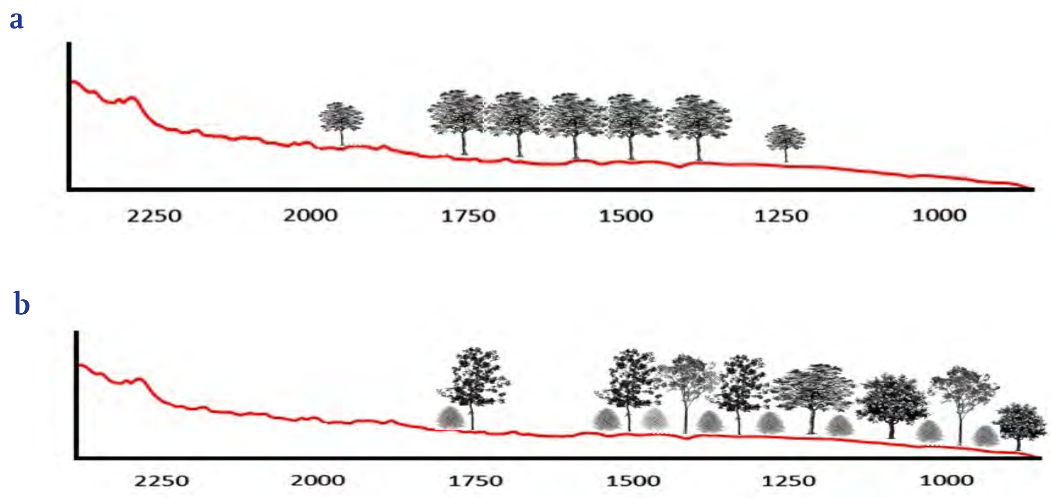
In terms of elevation, avocado crops are established between 1 250 and 2 250 m.a.s.l. However, 81.9 % (480.2 ha) of the crops are located between 1 250 and 1 750 m.a.s.l., with 66.6 % specifically found between 1 500 and 1 750 m.a.s.l. (Figure 4). Elevation has a direct influence on fruit morphology; avocados grown in lower areas (<1 300 m.a.s.l. tend to be rounder and with rougher skin compared to those grown under cooler climates at higher elevations, such as 2 400 m.a.s.l., where the fruit is more elongated with smoother skin (Bernal-Estrada et al., 2020). Therefore, the relationship between temperature and elevation suggests that, within the study area, the fruits typically display an oval shape with rough skin, traits that align well with current market demands. According to Bernal-Estrada et al. (2020), elevation also affects the flowering-to-harvest period. The elevations present in the study area support an intermediate harvest period ranging from 8 to 9 months, which is considered ideal for the Hass variety, thereby enabling optimal yields. Regarding slope, 97.8 % of the avocado plantations are established on slopes ranging from 0 to 8 %, which facilitates management activities. This agrees with the that reported by DANE (2016), which states that the ideal terrain slope for avocado crops should be less than 30 %, preferably with undulating topography, because this favors agronomic management.

Coffee

According to Gabriel-Hernández and Barradas (2024), coffee grown in Veracruz is found at elevations ranging from 300 to 3 000 meters above sea level (m.a.s.l.). The lower temperatures associated with higher elevations influence the coffee maturation period (Escamilla et al., 2016). In the study area, 94.4 % of the coffee plantations grow between 1 000 and 1 500 m.a.s.l., an optimal elevation range that promotes ideal maturation conditions and supports high yield potential (Figure 4). Additionally, elevation within the study area has a positive effect on the chemical composition of the coffee (flavor, body, and quality), allowing to produce high-quality specialty coffee for export (Bertrand et al., 2006).

Steep slopes are generally preferred for coffee cultivation, because they often overlap with areas of high biological diversity (Jiménez et al., 2023). As noted by Classen et al.

Figure 4. Semi-realistic profile of the distribution of reference crops by elevation range: (a) avocado (*Persea americana* var. Hass), (b) coffee (*Coffea arabica* var. Colombia and Costa Rica)



(2014), regions with greater plant diversity tend to support a richer community of pollinators, which can enhance agricultural productivity, particularly in coffee systems. Despite this, in the micro-watershed, 84.5 % of the coffee plantations are established on gentle slopes ranging from 0 to 4 %. This slope range does not negatively affect optimal coffee yields, as the crop exhibits high adaptability to the region's topographic conditions (Gabriel-Hernández & Barradas, 2024).

Type of soil

According to soil analysis, two additional soil types, distinct from those reported by INEGI, were identified: Cambic Andosol (AnCa) and Plinthic Acrisol (AcPl) (Figure 5). The most extensive soil type is Humic Andosol (AnHu), covering 71.7 % of the area, followed by Plinthic Acrisol with 12.5 % (Table 1). Orthic Acrisol (AcOr) is present to a lesser extent. These findings provide greater precision regarding soil distribution, which is essential for improving agricultural management and enabling comprehensive planning.

The values in Table 1 provide a comparative overview of the predominant biophysical conditions in areas cultivated with coffee and avocado. This integrated analysis allows for establishing a direct relationship between the evaluated variables to determine how they collectively influence crop growth and yield. For example, the combination of acidic soil, humid climate, and gentle slopes may create favorable conditions for pathogen development. Conversely, avocado achieves its greatest stability and productivity when grown on Humic Andosol soils, with slopes between 0 and 4 %, under a humid temperate climate.

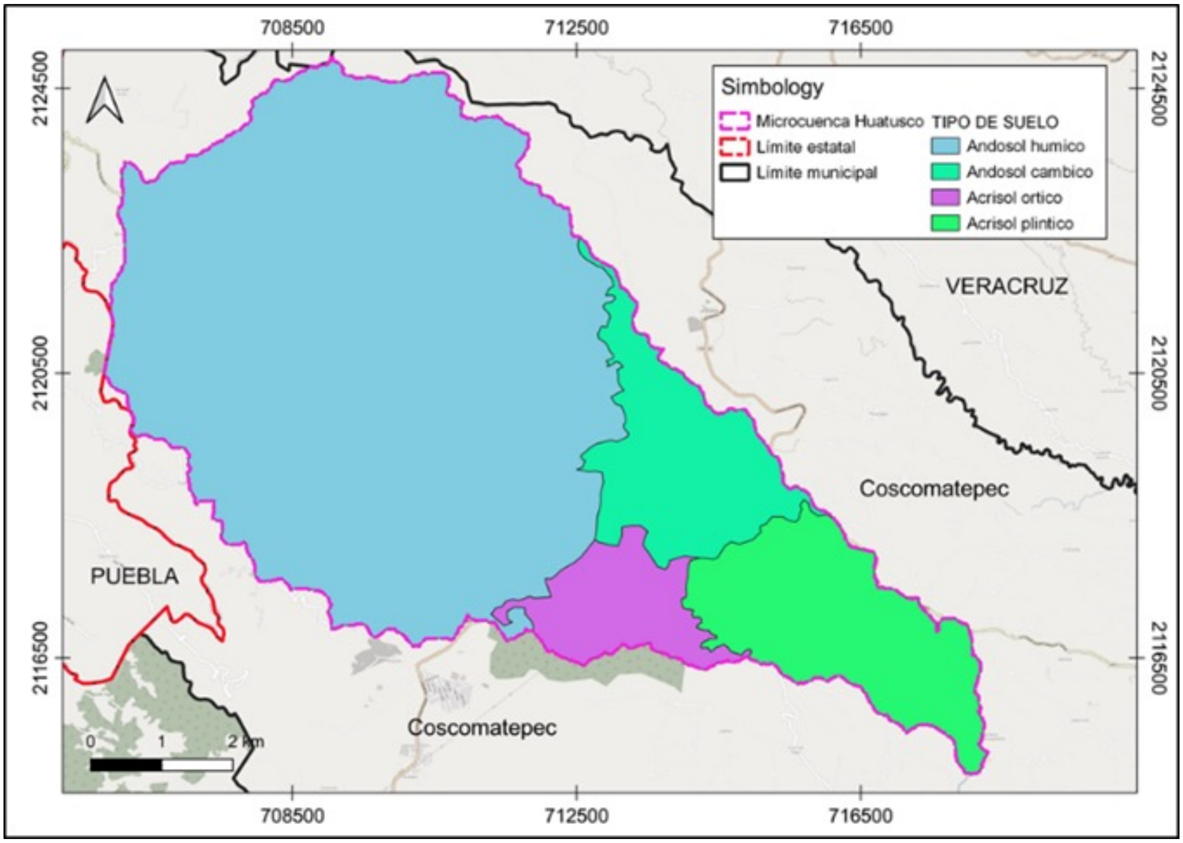
Avocado

The crop is predominantly established (99.6 %) in humic Andosol soils characterized by a pH of 5.2, a level that may limit nutrient availability and negatively affect yield. Despite this, the loamy-sand texture of the soil supports favorable water and nutrient retention (Table 2). Avocado trees are known to tolerate a wide range of soil types, from sandy to clay soils, although the latter are the most suitable. Optimal nutrient uptake typically occurs at a soil pH between 5.5 and 6.5 (Garrido-Ramírez, 2013; DANE, 2016). However, Salazar-García et al. (2009) observed pH values ranging from 4.7 to 6.4 in avocado orchards. Their research demonstrated that pH correction through lime application enhanced the absorption of key nutrients such as nitrogen, phosphorus, potassium, zinc, and boron, resulting in improved Hass avocado yields in Nayarit, even in non-irrigated systems.

Coffee

The predominant soils in coffee-growing areas are classified as Andosols with a pH ranging from 5.0 to 6.5 (Valencia & Rodríguez, 2016). However, according to the results, 53 % of coffee plantations are established on Acrisol soils, which showed more acidic pH levels than recommended (4.2-4.7), and are characterized by a predominantly clayey texture, low organic matter content, poor fertility, and drainage that ranges from moderate to poor. These conditions are reflected in a general decline in coffee productivity (Table 2). This finding is consistent with Sadeghian et al. (2019), who reported that high soil acidity reduces the availability of nitrogen, phosphorus, potassium, calcium, and magnesium, while increasing aluminum levels, which is toxic to plant roots and directly affect nutrient uptake. To compensate for these deficiencies, farmers apply both organic and chemical fertilizers, which contributes to increased production costs. Larios-González et al. (2014) highlighted that agroecological practices played a key role in stabilizing soil pH and mitigating active acidity, leading to improved soil fertility.

Figure 5. Soil types identified in the study area.



Source: Compiled by the authors.

Table 1. Area covered by reference crops in relation to biophysical variables.

Elevation (m.a.s.l.)		1000-1250	1250-1500	1500-1750	1750-2000	2000-2250
Area %	Ag	0	49.2	32.6	17.9	0.3
	Ca	47.1	47.2	5.6	0	0
Slope (%)		0-2	2-4	4-8	8-15	-
Area %	Ag	43.4	34.4	20	2.2	-
	Ca	60.1	29.4	9.5	1	-
Soil		AnHu	AnCa	AcOr	AcPl	-
Area %	Ag	99.6	0.4	0	0	-
	Ca	34.6	12.5	12.5	40.5	-
Climate		Humid temperate	Warm semi-humid	Warm semi-humid	Humid temperate	-
Area %	Ag	44.3	14.9	14.2	26.6	-
	Ca	8.6	77.2	9	5.3	

Note: Av: avocado; Co: coffee; AnHu: Humic andosol; AnCa: Cambic andosol; AcOr: Orthic acrisol; AcPl Plinthic acrisol

Based on the general analysis of the soil's chemical properties, the following can be determined: The EC values indicate that there are no salinity issues. The BD data suggests that the soils are organic and volcanic. Salamanca et al. (2005) highlight that and increase in BD leads to soil compaction, which generates unfavorable physical conditions that negatively affect coffee development during its early stages. The soil texture type is related to the amount of water retained at FC and PWP (Kramer & Boyer, 1996), as well as to the volume of water available for plants (Lambers et al., 1998).

Based on the above, it can be determined that humic andosol with loamy sand texture shows the highest field capacity (58.7 %) but also a relatively high permanent wilting point (34.8 %), resulting in 23.9 % plant-available water. Although its texture is coarser, the high porosity (61.3 %) and low bulk density (0.91 $g \cdot cm^{-3}$) indicate a good structure, typical of volcanic soils rich in organic matter. Plinthic acrisols, with a clayey texture, have a field capacity of 43.9 % and a permanent wilting point of 31.4 %, representing 12.5 % plant-available water. The cambic andosol has a loam texture, resulting in 18.9 % available water. Its bulk density is relatively high (0.99), which may limit aeration but remains favorable for root development. Lastly, the orthic acrisol, with a clay loam texture, has only 14.5 % available water. Although it has a finer texture, its BD=1 suggests soil compaction, which may reduce the total volume of usable water.

Characterization of agricultural crops

Avocado crop

Within the study area, only *Persea americana* var. Hass is grown as a commercial crop, because it has the highest demand in both national and international markets (Montealegre, 2014). Although avocado trees can reach up to 20 m in height (Bravo et al., 2009), in the study area, trees are kept at a height of 3 to 5 meters. The tree canopy is typically pruned into semicircular, semi-elliptical, or irregular shapes, with an average canopy diameter ranging from 4 to 6 m. The first harvest in this region generally occurs between 3 and 5 years after planting. However, this depends on the management practices applied during the plant's development (Campos et al., 2015) and on the origin of the planting material: grafted or seed-grown (Cruz-López et al., 2020).

Regarding orchard management, the following practices are primarily being implemented: pruning (for shaping, maintenance, and production), fertilization aimed at correcting soil acidity, irrigation to reduce water stress during the dry season, pest and disease control, weed management, and proper harvesting techniques.

The main issues affecting avocado production are caused by the seed borer (*Copturus aguacatae*), which significantly damages the fruit, leading to premature fruit drop or the development of deformities. Additionally, physical damage from hail is common, as well as size reduction and fruit abortion due to drought. Furthermore, producers face challenges related to price fluctuations. According to local growers, the avocado market is highly volatile. This crop is currently experiencing an economic crisis, as prices are no longer rising as they did in the past, while production costs continue to increase, placing the profitability of avocado crops at risk (Diaz, 2024).

Regarding climatic impacts, strong winds, heavy rainfall, and frost can lead to direct post-harvest fruit loss due to scarring. The increase in pathogenic organisms such as fungi and insects, mainly associated with excessive rainfall, especially during flowering stage, can result in diseases like anthracnose (Cruz et al., 2020), which directly affect crop yield.

To address the aforementioned issues, the implementation of an integrated pest management strategy is recommended, particularly for controlling the seed borer. One control method involves collecting and destroying infested fruit through burial or incineration. In addition, pruning host trees is necessary to reduce shading and promote proper aeration. For biological control, the use of entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* is advised. These fungi should be applied directly to the soil or tree stem (SENACICA, 2016). Application of these methods should be carried out during the critical period from July to October, when adult borers are active and fruits are developing (SAGARPA, 2005).

The use of chitosan, a natural fungicide derived from chitin, is recommended as a preventive method to combat anthracnose. It forms a protective film that inhibits fungal growth. It is recommended to apply it during flowering and fruit development, every 15 days throughout the rainy season, using foliar spraying (Munhuweyi et al., 2020) and to avoid excessive humidity within the plantations.

The adoption of localized irrigation techniques, particularly drip irrigation, is recommended as a strategy following the principles of Regulated Deficit Irrigation (RDI). This approach involves applying water supply below the crop's full potential requirements by restricting irrigation during specific phenological stages, without significantly affecting yield or product quality (Yang et al., 2022). For avocado and coffee crops, RDI can be implemented by limiting irrigation during the vegetative growth phase, when the crop can tolerate moderate water stress, and concentrating water supply during flowering of fruit filling stages. This approach helps maintain fruit quality while reducing total water consumption, without negatively impacting production. Gasque et al. (2016), demonstrated that the application of RDI in orange crops was able to save between 50 % and 55 % of water without affecting productivity. Additionally, it helped reduce fruit development issues and improve the commercial quality of citrus fruits.

Furthermore, protective measures should be implemented against wind, hail and frost. Lahak et al. (2024), found that covering young Hass avocado trees with 60 % shade netting during the winter season mitigates frost damage and improves tree performance. To prevent damage from hail and strong wind, Tapia et al. (2011) recommended establishing windbreaks, live fences, or planting companion trees to mitigate these impacts.

Coffee crop

Specifically, within the micro-watershed, only the species *Coffea arabica* is grown, predominantly established with the Colombia and Costa Rica varieties, which replaced the *Typica* variety starting in 2013. This change was due to the impact of coffee leaf rust (*Hemileia vastatrix*), leading producers to increase the presence of rust-resistant varieties (Escamilla et al., 2016).

Coffee crop in the studied area is classified as commercial, characterized by the use of native or introduced species with high commercial value that provide shade for the coffee plants (García et al., 2020). The tree species commonly associated with the coffee plantations include chalahuite or vainillo (*Inga vera*), cedar (*Cedrela odorata*), oak (*Quercus* sp.), avocado (*Persea americana*), ash (*Fraxinus uhdei*), macadamia (*Macadamia integrifolia*) and mango (*Mangifera indica*). It is important to note that fruit trees are harvested exclusively for self-consumption.

Coffee is a perennial shrub of tropical origin; however, it has successfully adapted to different ecosystems such as pine-oak forests and cloud forests (Toledo & Moguel, 1996). The Colombia and Costa Rica varieties show similar structures, both averaging heights of 2 to 2.5 meters and crown diameter of 1.5 to 2 meters. They are usually planted at a density of 3 500 plants$\cdot$ha^{-1}, arranged in staggered or square patterns with spacing of 1.5 to 2 meters between plants.

In relation to crop management, one of the main activities is the use of fertilizers: manures derived from livestock waste. However, it is recommended that these wastes be composted beforehand, as this process increases the content of Molybdenum, Nitrogen, Phophorus, Potassium and Magnesium, thereby producing a fertilizer with greater nutritional value (Pérez, 2008). As part of traditional practices, producers apply waste from coffee harvests, however, the study by Blagodatskaya & Kuzyakov (2013) indicates that its direct application is detrimental due to the high concentration of phenols and polyphenols in the coffee pulp, which are toxic substances for most arthropod species and microorganisms. Therefore, it is recommended to apply only 25 % coffee pulp in relation to the total compost volume (Cervantes Beyra et al., 2015). Other common management practices, according to producers, include weed control and tree pruning to regulate shade. Despite previous outbreaks of coffee leaf rust, 93 % of producers fail to carry out preventive pest or diseases control measures. The management of coffee farms is based solely on traditional techniques, with little to no use of agricultural technology, mainly due to a lack of financial resources and the prevailing landform (Bautista et al., 2018).

One of the main challenges faced by coffee crops is the gradual decline in available labor, primarily due to the migration of young people and the average age of producers, which is around 60 years. This situation represents a significant risk to the sustainability of coffee cultivation in the region, because the transmission of valuable local knowledge related to production is gradually being lost. This highlights the need to encourage younger generations to remain in rural areas through programs aimed at generational renewal. Additionally, actions should be taken to emphasize local traditions and cultural heritage so that coffee production can be sustained over time (Jiménez Barbosa et al., 2018).

On the other hand, coffee leaf rust remains a persistent phytosanitary threat that could lead to a further decline in grain production. This disease primarily affects old plantations that are nutrient-deficient and weakened by nematodes or other fungi (Hernández-Martínez & Velázquez-Premio, 2016). It is recommended to continue growing the Colombia and Costa Rica varieties, because they show resistance to coffee leaf rust (Escamilla et al., 2016).

According to Escamilla et al. (2005), additional damage can result from improper pruning of coffee plants and poor shade regulation. Furthermore, this year experienced a drought period that exceeded historically recorded ranges. Producers reported that the lack of rainfall during March and April affected the flowering cycle. In many cases, flowering was delayed until May, because it depends on the onset of the first rains to initiate the process. This delay caused a reduction in the number of flowers, which will likely be reflected in decreased grain production during the current harvest season. Therefore, it is recommended to establish the San Román variety, because it is drought-resistant. Additionally, it is proposed to complement this with moisture conservation techniques such as organic mulching and water harvesting structures, aligned with the principles of RDI (Yang et al., 2022). These measures aim to reduce production costs and increase resilience against the impacts of climate variability.

Overall diagnosis of coffee and avocado agricultural systems

By integrating biophysical variables and management practices, the following diagnosis is proposed for the evaluated crops: soil conditions are favorable for the development of coffee and avocado; however, there are key deficiencies that limit the yield and sustainability of these systems. These limitations are primarily related to: i) high soil acidity, especially in coffee-growing areas established on Acrisols, which reduces nutrient availability; ii) limited use of technologies for efficient water management, particularly during dry periods; iii) lack of preventive phytosanitary management, which increases production costs and vulnerability to diseases such as rust and anthracnose; and iv) low levels of mechanization, limited adoption of agroecological practices, and the progressive reduction of qualified labor.

Conclusions

The biophysical and descriptive characterization of shaded coffee and avocado crops allowed for the identification of environmental factors, agricultural practices, and socioeconomic factors that are directly influencing their production. Although these crops are fundamental to the regional economy, they continuously face challenges such as pests, diseases, climate variability, and inadequate resource management, among others, which could compromise their viability and productivity.

The Hass avocado variety has significant potential to expand its planted area within the micro-watershed, because the biophysical conditions are favorable for its establishment. The crop is grown on humic andosols; a soil type possesses suitable characteristic for water retention and availability. However, the crop faces challenges that impact productivity, mainly related to soil acidity, which limits nutrient availability, and phytosanitary issues such as the seed borer and anthracnose, that become more severe in the presence of excess moisture.

To counteract these challenges, it is recommended to implement management practices aimed at correcting soil pH through the application of inputs accessible to producers, such as lime and compost. The use of natural preparations, including chitosan and entomopathogenic fungi, is also advised. Additionally, establishing localized irrigation based on the principles of RDI, and physically protecting the crop from environmental stresses such as hail, wind and frost through windbreaks and shade net, are recommended. These measures will help optimize productivity, reduce production costs and secure the long-term sustainability of the crop in response to environmental and economic variability.

While 94.4% of coffee is cultivated in regions with ideal elevations, slopes, and climates for optimal growth, soil type remains a major limiting factor. Over half of all coffee crops are grown on acrisols, oils that are acidic, clayey in texture, low in fertility, and poorly drained. These conditions reduce nutrient availability and increase exchangeable aluminum levels, which negatively impact the root system and nutrient uptake. As a result, farmers are compelled to use corrective input, leading to higher production costs.

Therefore, it is necessary to apply pre-composted organic fertilizers and include only 25 % coffee pulp in the total volume to correct acidity issues and improve soil fertility. It is important to continue establishing rust-resistant varieties such as Colombia and Costa Rica. The progressive loss of labor, which threatens the sustainability of coffee cultivation, can be addressed through government programs or private initiatives aimed at generational renewal. One strategy to combat drought is the introduction of the San Román variety and the implementation of moisture conservation techniques under the RDI approach, to reduce the impact of climate variability and thereby improve profitability, productivity, and the long-term sustainability of coffee production.

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