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Articulo Original

Physical characterization of soil profiles from the main avocado *(Persea americana Mill)* producing areas in Ecuador

Caracterización física de perfiles de suelos de las principales zonas productoras de aguacate *(Persea americana Mill)* en Ecuador

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Abstract

***Objectives*:** The objective of this study was to physically characterize soil profiles from 7 commercial orchards of the Hass and Fuerte avocado varieties, grafted onto National and Zutano rootstocks, in the main avocado-producing provinces of Ecuador: Carchi (C), Imbabura (I), Pichincha (P), Tungurahua (T), and Santa Elena (SE). ***Methodology*:** Soil pits were dug in each study area, and soil profile horizons were sampled and characterized through field-based physical analysis. Yield data by variety were collected from orchard owners and/or technicians**.** ***Results*:** The results showed a higher use of National (Mexican) rootstocks, and identified four optimal locations from an edaphic perspective (San Vicente-P, Yachay-I, San Joaquín-I, Tomebamba-I), based on effective depth, texture, structure, and salinity. With adequate agronomic management (pH reduction and organic matter addition), these areas could generate high yields and exportable quality crops. Two zones (Písquer-C and Los Andes-T) were identified where amendments (increased organic matter, pH reduction, and salinity control) and physical soil corrections (increased effective depth and structuring) could create suitable conditions for avocado production. One area (El Azúcar-SE) were classified as unsuitable for avocado cultivation due to shallow effective depth (15 cm), clayey textures (> 89%), massive structuring, alkaline pH (> 8.45), and saline soils (2.74 mS cm^{-1}). ***Conclusions*:** The soils intended for avocado cultivation are diverse, and in some cases, do not meet the necessary physical requirements. The use of sexually propagated National (Mexican) rootstocks is common in Ecuador, but soil variability and limiting conditions are not always taken into account. For areas with mild edaphic restrictions, conditioning and amendments are necessary.

Keywords: Soil pit, Physical soil characterization, Soil profile, Rootstock, Avocado.

Resumen

***Objetivos*:** El objetivo de este estudio fue caracterizar físicamente los perfiles de suelo de 7 huertos comerciales de las variedades Hass y Fuerte, injertados en portainjertos Nacional y Zutano, en las principales provincias productoras de aguacate de Ecuador: Carchi (C), Imbabura (I), Pichincha (P), Tungurahua (T) y Santa Elena (SE). ***Metodología*:** Se realizaron calicatas en cada área de estudio, se tomaron y caracterizaron los horizontes del perfil del suelo mediante análisis físico en campo. Los datos de rendimiento por variedad fueron recolectados de los propietarios de huertos y/o técnicos. ***Resultados*:** Los resultados mostraron un mayor uso de portainjertos Nacional (mexicano) e identificaron cuatro ubicaciones óptimas desde una perspectiva edáfica (San Vicente-P, Yachay-I, San Joaquín-I, Tomebamba-I), basadas en la profundidad efectiva, textura, estructura y salinidad. Con una adecuada gestión agronómica (reducción del pH y adición de materia orgánica), estas áreas podrían generar altos rendimientos y cultivos de calidad exportable. Se identificaron dos zonas (Písquer-C y Los Andes-T) donde las enmiendas (aumento de materia orgánica, reducción de pH y control de salinidad) y correcciones físicas del suelo (aumento de la profundidad efectiva y estructuración) podrían crear condiciones adecuadas para la producción de aguacate. Una zona (El Azúcar-SE) fue clasificada como no adecuada para el cultivo de aguacate debido a la baja profundidad efectiva (15 cm), texturas arcillosas (> 89%), estructuración masiva, pH alcalino (> 8.45) y suelos salinos (2.74 mS cm^{-1}). ***Conclusiones*:** Los suelos destinados al cultivo de aguacate son diversos y, en algunos casos, no cumplen con los requisitos físicos necesarios. El uso de portainjertos Nacional (mexicano) propagados sexualmente es común en Ecuador, pero la variabilidad del suelo y las condiciones limitantes no siempre se tienen en cuenta. Para las áreas con restricciones edáficas leves, son necesarios el acondicionamiento y las enmiendas.

Palabras clave: Calicata, Caracterización física del suelo, Perfil de suelo, Portainjerto, Palta.

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Introduction

The avocado (*Persea americana* Mill) has become an important alternative for diversifying Ecuador's export products (Viera et al., 2016). In 2023, Ecuador exported 1,638 tons worth 2.9 million dollars, benefiting 12,889 producers. The crop is grown across 4,550 hectares in provinces such as Carchi, Pichincha, Imbabura, Tungurahua, Santa Elena, and Guayas, with a national yield of 5.83 tons per hectare (MAG, 2023). Avocado adapts to various soil types, from sandy to clayey, with an ideal soil depth of 0.8 to 1.0 meters and a pH range of 5.5 to 6.5 to ensure proper nutrient absorption (Garrido et al., 2013).

The avocado tree is native to the coastal and montane rainforests of Mesoamerica (Schaffer et al., 2015; Solares et al., 2023) and belongs to the Lauraceae family and Persea genus (Bergh, 1992). There are three varieties of avocado: Mexican, Antillean, and Guatemalan, each differing in morphology and adaptability to soil and climate conditions. The avocado root system consists of a main root and shallow secondary roots that absorb water and nutrients for growth, with root growth occurring in the form of flows, influenced by factors like soil texture, compaction, pore space, and moisture (Salazar-García, 2002; Salazar-García & Cortés-Flores, 1986). Soil temperature also plays a key role in root growth efficiency (Salazar-García, 2002).

Avocados are sensitive to drought, extreme temperatures, and salinity, particularly the Mexican variety. Poor aeration caused by heavy soils can also negatively impact growth, as continuous rainfall can lead to root rot caused by the *Phytophthora cinnamomi* fungus, which thrives in poorly drained soils with low pH (Ben-Ya'acov and Michelson, 1995). Ecuador's volcanic soils, covering about 31% of the country, are a valuable agricultural resource, known for their high productivity (Takahashi & Shoji, 2002; García and Schlatter, 2012). Successful crop development depends on the quality of the site, including climate and soil conditions.

A technique known as "calicata" or “pit” involves excavating a soil volume to analyze its profile, layers, groundwater depth, and root health, identifying limiting factors for crop productivity (Viera Martinez et al., 2008; Calderón et al., 2016). This method is crucial for understanding soil conditions and suggesting improvements. The aim of this research was to characterize the soils of ten commercial avocado orchards in Ecuador to identify limiting soil factors and recommend corrective practices to enhance avocado productivity.

Methodology

Location and description of study areas

Table 1 and Figure 1 detail and observe the political-geographical locations and climatic characteristics of the orchards studied.

Table 1

Political-geographical locations and climatic characteristics of the localities where avocado orchards studied in 5 provinces of Ecuador are located

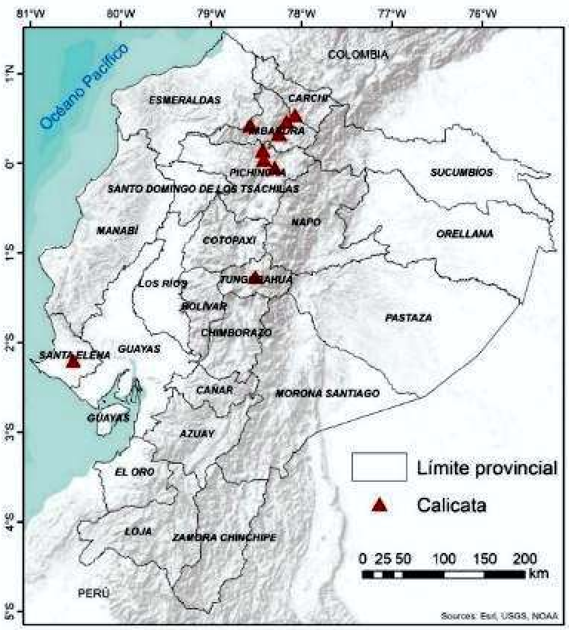
Code	Locality (area, parish, canton, province)*	Geographical coordinates**			Weather conditions***			
		X (m)	Y (m)	Z (masl)	Annual precipitation (mm)	Average annual temperature (°C)	Annual evapotranspiration(mm)	Annual water deficit (mm)
L1	Pisquer, Mira, Mira, Carchi	825736	10059273	2345	450	16,5	825	-165
L2	San Joaquín, Cuellaje, Cotacachi, Imbabura	770796	10046471	2316	1850	16,5	875	5
L3	Yachay INIAP, Tumbabiro, Urcuquí, Imbabura	815786	10051394	1904	750	18,5	875	-205
L4	Tomebamba, Cotacachi, Cotacachi, Imbabura	805510	10036053	2402	1150	16,5	675	65
L5	San Vicente, Guayllabamba, Quito, Pichincha	801134	9994480	2517	750	15,5	725	75
L6	Los Andes, Los Andes, Patate,Tungurahua	777098	9859957	2257	650	15,5	725	-15
L7	El Azucar, Colonche, SantaElena, SantaElena	552798	9756888	56	450	25,5	1275	-813

* CONALI (2021). ** World Geodetic System 1984 (WGS84). *** Series 1985-2009 (IGM, 2023)

The evapotranspiration and annual water deficit were calculated by the Thornthwaite method and information from nearby meteorological stations. In the case of evapotranspiration, the monthly average temperature was used and the annual water deficit was constructed from the income (median precipitation) and outflows (evapotranspiration), through a calculation that includes as an intermediary the soil with its maximum water retention (300 mm), using monthly values from a series of the last 25 years (1985-2009) (MIDENA et al., 2013; IGM, 2023).

Figure 1

Geographic location of 7 orchards analyzed, in 5 provinces of Ecuador (Carchi, Imbabura, Pichincha, Tungurahua and Santa Elena)



Soil samping and analysis

Selection of orchards

It corresponds to 7 orchards representative of each producing area located in 5 provinces (Carchi, Imbabura, Pichincha, Tungurahua and Santa Elena). The ages of the orchards varied between 4 and 40 years, all had drip irrigation systems except Guayllabamba (L8) and Los Andes (L9) which had gravity irrigation. For the most part, fertilizers are applied at the edaphic level with the exception of the orchard located in the province of Santa Elena (L10) that had a fertigation system (Table 2).

Table 2

Main agronomic characteristics of 7 orchards studied in 5 provinces of Ecuado

Code	Locality (area, parish, canton, province)	Area (ha)*	Plantation frame (m*)	Age (years) *	Irrigation systems
L1	Pisquer, Mira, Mira, Carchi	30	4*4	12	Drip
L2	San Joaquín, Cuellaje, Cotacachi, Imbabura	4	6*6	4	Drip
L3	Yachay INIAP, Tumbabiro, Urcuquí, Imbabura	2	5*4	5	Drip
L4	Tomebamba, Cotacachi, Cotacachi, Imbabura	3	5*6	12	Drip
L5	San Vicente, Guayllabamba, Quito, Pichincha	5	7*7	40	Gravity
L6	Los Andes, Los Andes, Patate, Tungurahua	5	5*5	6	Gravity
L7	El Azúcar, Colonche, Santa Elena, Santa Elena	60	4*6	4	Drip, fertirrigation

*Information generated from consultations with owners and technicians of each orchard

Description of soils using pits

The physical study of the soil profile was carried out using pits with dimensions: 1.5 m long, 1 m wide and 1 m deep. The methodology for soil description and sampling of Schoeneberger et al. (2002) was used, and the FAO Soil Description Guide (2009). In general, the variables were recorded: slope (%), surface stoniness (%), drainage (scale), water table (scale) and total effective depth (cm), the latter characteristic being the distance from the surface to a compact layer or cemented with clay, bedrock or other materials, which prevent the free growth of roots, water infiltration and rise of the water table.

Specifically, each horizon present in the soil profile was identified and its depth (cm), texture and structure in the field (scales), wet color (Munsell table), humidity (%), salinity (mS cm^{-1}) measured. with a TDR 150 equipment (20 cm probe, Fieldscout) without determining the chloride content. Also, samples of 1 kg of soil were taken from each horizon to be analyzed physicochemically in the laboratory. The information was recorded on soil description sheets for each orchard.

Analysis of samples in the laboratory

pH, organic matter content (%) were determined from each horizon

Soil classificationtion

According to soil characteristics determined through pit and soil taxonomy studies (Soil Survey. 2022).

Other agronomic variables

The variables were determined through interviews with the owners, administrators, and technicians of the orchards studied and direct observation in the field: cultivated crown and rootstock variety and average annual yields (kg tree $^{-1}$ and t ha $^{-1}$).

Results and discussion

General characteristics of fruit orchards

In the Ecuadorian highlands (1897 to 2517 meters above sea level), both in orchards studied and surrounding ones, the prevalent use of "Nacional" or "Criollo" rootstocks, belonging to the Mexican breed, was noted. These rootstocks are sexually propagated and identifiable by their characteristic anise odor (Gutiérrez-Díez et al., 2015). Exceptions were the orchard in locality 3, which had "Mexican hybrids" and the orchard in locality 7, with Zutano variety rootstocks from seeds. The cultivated varieties were Fuerte and Hass, with Fuerte being dominant in the mountains and aimed at the national market, while Hass is grown on a smaller scale for an emerging international market. The average annual yield of all orchards studied was 9.35 t ha^{-1} (20.50 kg tree^{-1}), surpassing the national average of 6.11 t ha^{-1} (MAG, 2023), but lower than other countries like Mexico (10.76 t ha^{-1}), Colombia (11.41 t ha^{-1}), and Peru (15.00 t ha^{-1}) (MAG, 2023). Fuerte achieved 12.30 t ha^{-1}, higher than reports from Mexico and Ethiopia (Samaniego-Ruso & Sánchez-Sánchez, 1999; Sora, 2023). Hass yielded 8.38 t ha^{-1}, lower than Mexico (9.7 t ha^{-1}) and California (11.68 t ha^{-1}) (Lovatt et al., 2015), but higher than Colombia's productivity (8.00 t ha^{-1}) (Samaniego-Ruso & Sánchez-Sánchez, 1999; Cano-Gallego et al., 2023). These yields are still far from the potential of Hass, which can reach 28-30 t ha^{-1} (Salazar-García et al., 2009). The orchard with hybrid Mexican race plants (locality 3) had a yield of 9.7 kg tree^{-1} (4.2 t ha^{-1}), similar to Mexícola rootstocks (9.33 kg tree^{-1}) but lower than cosmopolitan Duke series plants (26 kg tree^{-1}) (Avilán & Rodríguez, 1997). These rootstocks are now evaluated as suitable for the local edaphoclimatic conditions. The orchards displayed heterogeneity, with trees of varying heights and crown volumes, even though they were of the same age, variety, management, and edaphoclimatic conditions. This variability is attributed to the use of Mexican rootstocks, which due to open pollination and protogyny dichogamy, exhibit heterozygosity and morphological differences that affect the resulting top variety (Ben-Ya'acov & Michelson, 1995; De Villiers & Ernst, 2015).

Table 3

Agronomic and productive characterization of 7 orchards studied in 5 provinces of Ecuador

Code	Locality (area, parish, canton, province)	Variety		Yield	
		rootstock	tree top	kg tree^{-1}	t ha^{-1}
L1	Pisquer, Mira, Mira, Carchi	Nacional	Fuerte, Hass	19.20	12.0
L2	San Joaquín, Cuellaje, Cotacachi, Imbabura	Nacional	Hass	15.12	4.20
L3	Yachay INIAP, Tumbabiro, Urcuquí, Imbabura	without grafting plants	mexican hybrids	9.7	4.85
L4	Tomebamba, Cotacachi, Cotacachi, Imbabura	Nacional	Hass	51.0	17.0
L5	San Vicente, Guayllabamba, Quito, Pichincha	Nacional	Fuerte	24.0	15.0
L6	Los Andes, Los Andes, Patate,Tungurahua	Nacional	Hass	13.28	5.31
L7	El Azúcar, Colonche, Santa Elena, Santa Elena	Zutano	Hass	11.20	7.0

Specific characterization of fruit orchards, oil and climate

Table 4 present the main physical characteristics of the soils studied with variables recorded in the soil profile through pits

Table 4

Variables recorded through a study of 1 m deep pits, in 7 orchards and 5 main avocado producing provinces in Ecuador.

Profile code	Locality (area, parish, canton, province)	Soil classification*	Earring (%)	Surface stoniness (%)	Drainage (scale)	Water table (scale)	Total effective depth (cm)	Horizon	Horizon depth (cm)	Wet color (Munsell scale)	Texture in field	Structure	Humidity (%)	Electrical conductivity (mS cm^{-1})	Organic matter (%)	pH
L1	Pisquer, Mira, Mira, Carchi	Mollisols	25-40	0	Well	No evidence	40	TO	0-40	7.5YR 3/2	Frank	Granular to subangular blocks	28.5	0.22	1,49	7,53
				0				c	>40	10YR 4/2	sandy loam	Without Structure	28.5	0.22	0.73	7.59
								C1	20-80	10YR 2/2	Loamy sand	Without Structure	24.1	0.13	0,82	8,00
								C2	>80	10YR 3/2	Sandy	Without Structure	6.8	0	0,51	7,91
L2	San Joaquin, Cuellaje, Cotacachi, Imbabura	Inceptisols	70-100	0	Well	No evidence	70	TO	0-40	10YR 2/1	Frank	Granular to subangular blocks	10.8	0	13,67	5,24
								bw	40-70	10YR 3/3	Clay loam	Subangular blocks	10.1	0	6,62	5,88
								c	>70	10YR 3/4	Clay loam	Without Structure	12.3	0.04	4.83	5.72
L3	Yachay INIAP, Tumbabiro, Urcuqui, Imbabura	Mollisols	25-40	0	Well	No evidence	>100	A1	0-15	10YR 2/2	Frank	Granular to subangular blocks	5.6	0	2,51	8,00
								A2	>15	10YR 3/2	sandy loam	Subangular blocks	7.6	0.03	0.38	9.01
L4	Tomebamba, Cotacachi, Cotacachi, Imbabura	Mollisols	5-dic	0	Well	No evidence	>100	A1	0-20	10YR 2/1	Frank	Granular to subangular blocks	--	--	3,06	7,30
								A2	20-65	10YR 2/2	Frank	Subangular blocks	--	--	2,03	7,23
								A3	>65	7.5YR 2.5/1	Loamy sand	Subangular blocks	--	--	0,61	7,57
L5	San Vicente, Guayllabamba, Quito, Pichincha	Entisols	5-dic	0	Well	No evidence	>100	A1	0-15	10YR 2/2	Sandy	Granular to subangular blocks	7.3	0	1,25	7,30
								C1	15-40	7.5YR 3/2	Sandy	Without Structure	15.4	0.02	0,59	7,67
								C2	40-70	10YR 3/2	Loamy sand	Without Structure	19.4	0.05	0,38	7,58
								Ab	>70	7.5YR 3/2	Frank	Subangular blocks	20.9	0.08	0.56	7.42
L6	Los Andes, Los Andes, Patate, Tungurahua	Mollisols	5-dic	5	Well	No evidence	55	A1	0-15	7.5YR 2.5/1	Frank	Granular	22.7	0.08	4,79	7,23
								A2	15-55	7.5YR 3/2	sandy loam	Subangular blocks	21.8	0.11	1,47	7,85
								bt	>55	7.5YR 3/2	Sandy clay loam	Subangular blocks	21.8	0.11	0,99	7,99
L7	El Azucar, Colonche, Santa Elena, Santa Elena	Vertisols	5-dic	0	Deficient	No evidence	15	TO	0-15	2.5Y 4/2	Silty clay	Granular to subangular blocks	41.9	1.03	1,20	8,45
								C1	15-40	2.5Y 4/2	Silty clay	Massive	50.5	1.42	0,77	8,50
								C2	>40	2.5Y 4/2	Silty clay	Massive	54.5	2.74	0,76	8,5

Location 1

Located in the province of Carchi, Mira canton and parish, Písquer locality, it is the orchard studied in the mountain range with the largest area (30 ha), with equal parts of Hass and Fuerte varieties (625 trees ha $^{-1}$), 12 years old, planted at the foot of a slope. It has an average annual yield of 12 t ha $^{-1}$ (19.20 kg tree $^{-1}$), the third highest among the studied plots, and higher than national (6.11 t ha $^{-1}$) and provincial (6.76 t ha $^{-1}$) yields (MAG, 2023). The trees exhibited poor vigor, with heights of 2.5-3 m, sparse foliage, and sunburn on some fruits, resulting in about 5% tree mortality.

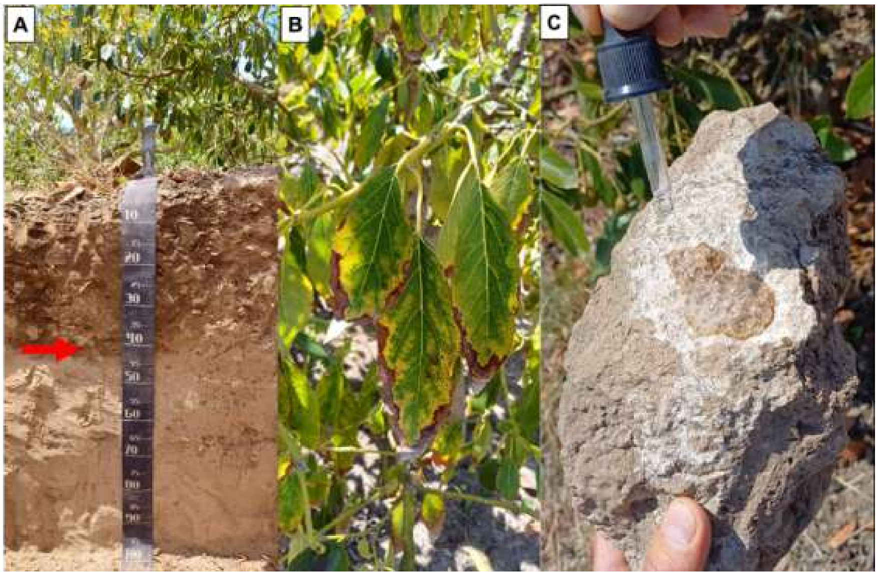
Figure 2

A. Tree of 12-year-old Hass-Nacional varieties, with medium vigor and little foliage (≈ 2.5 m), B. Sunstroke on Hass fruit caused by little foliage on the tree. Province of Carchi, Mira canton, Písquer parish.

The soil was classified as Mollisols (Soil Survey, 2022), with an effective depth of 40 cm and a loamy texture in the A horizon (sand 42%, silt 39%, clay 19%). Below 40 cm, a compact C horizon was detected, limiting root growth and potentially affecting drainage during heavy rains (Durand & Claassens, 1987). Despite these challenges, no evidence of water table rise or hypoxia processes was found, likely due to low precipitation (450 mm), high evapotranspiration (825 mm) (Table 1), and good infiltration characteristics of the A horizon. The organic matter content was low (1.11%), below the 2-6% range recommended for avocado trees (Dubrovina & Bautista, 2014; Schaffer et al., 2015), and decreased to 0.73% in the C horizon. The electrical conductivity was 0.22 mS cm $^{-1}$, lower than the threshold for yield reduction (0.75 mS cm $^{-1}$) (Acosta-Rangel et al., 2019). The pH (7.53-7.59) exceeded tolerable levels for Mexican ecotype rootstocks, affecting micronutrient absorption and potentially causing iron chlorosis (Wolstenholme, 2003; Bender et al., 2012). Leaf damage included chlorosis, likely due to carbonates (Figure 3). To address these issues, the use of acidifiers, iron chelates, organic matter, or Antillean rootstocks (Ben-Ya'acov & Michelson, 1995; Wolstenholme, 2003) is recommended, with further evaluation of these rootstocks in similar areas.

Figure 3

A. Variation of the soil profile from an A horizon with a depth of 40 cm (effective depth) and subsequent transition (red arrow) to a compact C horizon that exceeds 100 cm in depth. B. Advanced damage to leaves probably due to soil conditions (alkalinity) 3 inadequate use of rootstocks. C. Reaction of an HCl solution with carbonates present in the horizon C. Province of Carchi, Mira canton, Písquer parish.



Location 2

The orchard located in San Joaquín, 6 de Julio de Cuellaje parish, Cotacachi canton, Imbabura province, covered approximately 4 ha, planted with Hass variety trees (277 trees ha $^{-1}$) on a slope of 85%, the steepest recorded in this study (Figure 4A). The producer reported a yield of 4.2 t ha^{-1} (15.1 kg tree $^{-1}$), which is lower than national and provincial yields (MAG, 2023), but the tree age (4 years) must be considered. Similar yields were observed in other studies with younger orchards (Menzel & Le Lagadec, 2014). The orchard's general appearance was vigorous, with abundant foliage, good annual regrowth, 4 m tall trees, and less than 2% tree mortality.

The soil was classified as Inceptisol (Soil Survey, 2022) with good drainage and no evidence of a water table. The effective depth was 70 cm, comprising A (0-40 cm) and Bw (40-70 cm) horizons with loamy and sandy loam textures, respectively, contributing to good soil aeration and root growth (Salazar-García and Lazcano-Ferrat, 2002; Crowley, 2007). However, the C horizon was compact, with silty loam texture, potentially limiting root development.

This area had the highest precipitation (1850 mm) among the studied orchards (Table 1), which, combined with the soil texture, could lead to nutrient leaching (Viteri et al., 2023). The soil had low salinity, moderately acidic pH (5.61), and high organic matter content (8.37%), especially in the A horizon (13%), which benefits avocado root development by improving soil aeration and moisture retention (Grunennvaldt, 2022).

The high organic matter content aligns with the avocado tree's origins in humid cloud forests, where it depends on organic matter decomposition for nutrient absorption (Salazar-García, 2002; Menzel & Le Lagadec, 2014; Schaffer et al., 2015; Sotomayor et al., 2022). The pH, near the lower optimal limit (5.5) (Dubrovina & Bautista, 2014), may decrease over time due to rainfall, and excessive acidification should be avoided to prevent issues like bacterial nitrification disruption and nutrient deficiencies (Bender and Faber, 1999; Wolstenholme, 2003; Osorio, 2012). If the pH drops below 5.2, micronutrient toxicity from aluminum and manganese could affect plant health (Ben-Ya'acov & Michelson, 1995; Osorio, 2012; González-Vences et al., 2024).

Figure 4

A. Orchard of the Hass-Nacional variety planted on hills with a slope $\bar{x}$=85 B. Soil profile with an effective depth of 70 cm (loam, sandy loam) and abundant presence of suberized roots at a depth of 1 m (Red Arrow). Province of Imbabura, Cotacachi canton, Seis de Julio de Cuellaje parish.

Location 3

The orchard located at the Yachay-INIAP Experimental Farm in Tumbabiro parish, Urcuquí canton, Imbabura province, covered approximately 2 ha (500 trees ha^{-1}), planted with 5-year-old hybrids of the Mexican race (Figure 5). The trees, with heights of 3 to 4 m, yielded 4.85 t ha^{-1} (9.7 kg tree^{-1}) annually, with vigorous growth, good regrowth, and low mortality (<2%), despite alkaline soil conditions.

Figure 5.

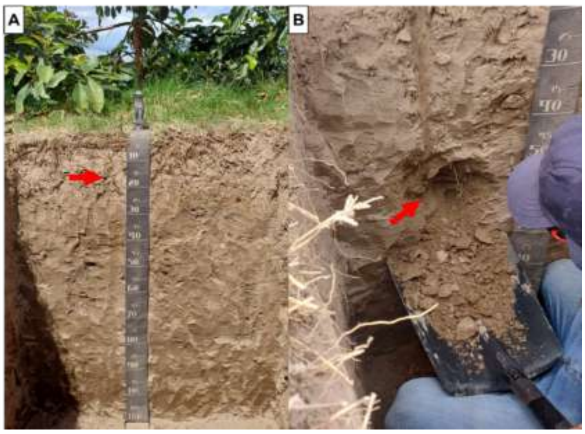
Orchard made up of trees from seeds of hybrids of the Mexican race evaluated for alkaline soil conditions. Province of Imbabura, Cotacachi canton, Tumbabiro parish, Yachay Experimental Farm.

The soil was classified as Mollisols (Soil Survey, 2022) and showed no evidence of a high or constant water table. It had an effective depth greater than 100 cm, with A1 (0-15 cm) and A2 (>15 cm) horizons, both having sandy loam textures (sand 60%, silt 29%, clay 11%) and granular structures (Table 4, Figure 6A). The soil exhibited good drainage and aeration, promoting healthy root development (Salazar-García & Lazcano-Ferrat, 2005; Crowley, 2007; Schaffer et al., 2015). Salinity levels were below 0.03 mS cm $^{-1}$, which did not limit avocado production (Acosta-Rangel et al., 2019). However, the pH, ranging from 8 in A1 to 9 in A2, was high and could pose challenges for Mexican rootstocks, which prefer moderately acidic, organic-rich soils (Rebolledo-Roa and Burbano-Díaz, 2023). Alkaline pH can lead to microelement blockage and iron chlorosis, although no visible symptoms were observed in these trees (Kourgialas & Dokou, 2021).

The soil's organic matter content was low (average 1.45%), decreasing from 2.51% in A1 to 0.51% in A2. This low organic matter and clay content could affect the soil's cation exchange capacity and water retention, necessitating organic matter additions and controlled irrigation (Crowley, 2007; Sotelo-Nava et al., 2017). To address the soil's limitations, pH correction is recommended, along with organic matter additions, fertigation, and acidifying fertilizers (Grunennvaldt, 2022; Granja & Covarrubias, 2018; Bender &Faber, 1999). Foliar applications with chelated products could help prevent microelement deficiencies (Lovatt, 2013).

Figure 6

A. Soil with effective depth >100 cm (sandy loam), red arrow marks transition between horizons A1 and A2, B. abundant presence of suberized and non-suberized roots at 80 cm depth. Province of Imbabura, Cotacachi canton, Tumbabiro parish.



Location 4

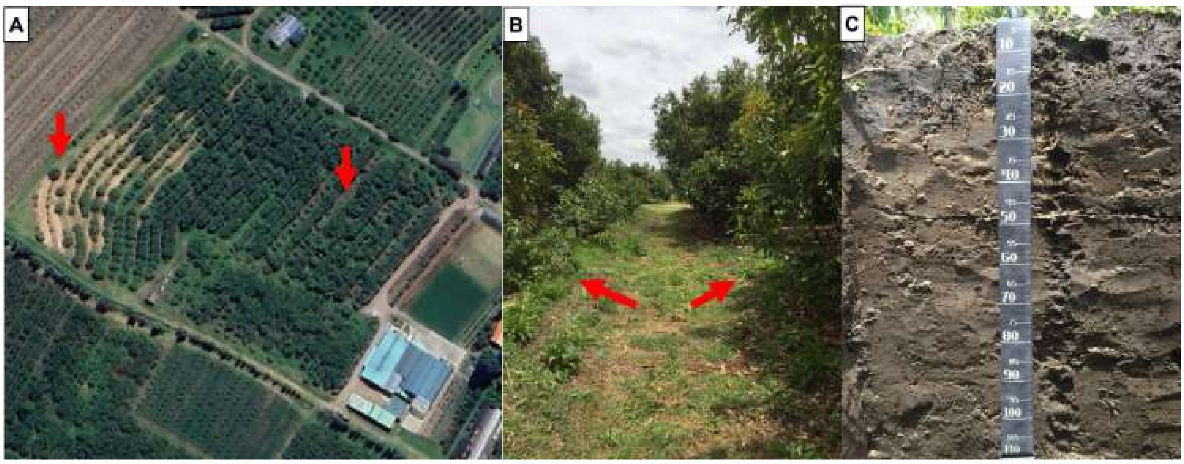
The orchard, located in the Tomebamba locality, Cotacachi canton, Imbabura province, covered approximately 3 ha (333 trees ha $^{-1}$) and consisted of 12-year-old Hass plants. With tree heights over 4 m, the orchard had a mortality rate exceeding 10% but displayed vigorous growth and good annual regrowth (Figure 7A). The reported annual yield was 17 t ha $^{-1}$ (51 kg tree $^{-1}$), the highest in the study, surpassing national and provincial averages (MAG, 2023). Similar yields have been observed in Colombia (Hass-Criollos Antillanos) with harvests between 38-56 kg tree $^{-1}$ (Rebolledo & Burbano, 2023), and in California (Hass variety) with an average of 51 kg tree $^{-1}$ (Lovatt et al., 2015).

The soil was classified as Mollisols (Soil Survey, 2022) and was unique in this study as planting was done in mounds (≈0.6 m height, ≈2 m base width, ≈1 m top width), which improved soil characteristics such as drainage, aeration, and root growth space (Figure 7B). This technique, used since the 1940s in California to address restrictive soil conditions (Pillsbury & Huberty, 1944), is also recommended for avocado cultivation in soils with poor drainage and shallow depths (Grunennvaldt, 2022).

The soil had an effective depth greater than 100 cm, consisting of three horizons: A1 (0-20 cm), A2 (20-65 cm), and A3 (>65 cm). The first two horizons had sandy loam textures (sand 54%, silt 26%, clay 20%), while the third had a loamy texture. Granular and subangular block structures were observed in the horizons (Figure 7C, Table 4). The presence of roots throughout the profile indicated optimal conditions for avocado root growth, which can extend up to 2 m in deep, non-restrictive soils (Durand & Claassens, 1987). The clay content (20%) in the top two horizons enhanced soil fertility and cation exchange capacity (Sotelo-Nava et al., 2017). The average soil pH was slightly alkaline (7.37), which should be corrected to fall within the optimal pH range for avocado trees (5.5-6.5) to improve nutrient availability (Schaffer et al., 2015; Dubrovina & Bautista, 2023). The organic matter content in the A1 horizon was 3.06%, within desirable thresholds, benefiting tree nutrition due to the avocado's evolution in neotropical cloud forests with abundant leaf litter and plant remains (Salazar-García, 2002; Menzel & Le Lagadec, 2014).

Figure 7

A. Orchard of Hass-Nacional varieties with mortality greater than 15% B (Google Earth, 07-19-2023). B. Trees planted in mounds (red arrows) to improve effective depth, drainage capacity, aeration and other soil characteristics, C. Soil with effective depth >100 cm and 3 horizons (A1, A2, A3) with sandy loam textures and frank. Province of Imbabura, Cotacachi canton, Cotacachi parish.



To compare these results, we made another pit in an orchard without the use of soil mounds. This orchard was located in Perafán, Imantag parish, Cotacachi canton, Imbabura province (distance between sites ≈870 m). It consisted of Fuerte-Nacional variety trees, 5 years old, planted on lands with a low slope. The soil was classified as Mollisols (Soil Survey, 2022) with moderate drainage capacity, despite the low slope (8.5%) and high annual precipitation (1050 mm). The soil profile had three horizons, all with sandy loam texture (sand 62%, silt 24%, clay 13.66%), which likely helped prevent floating layers. The effective soil depth was 20 cm, with good structuring in the A horizon, while the C1 (20-80 cm) and C2 (>80 cm) horizons were compact, restricting root growth and the orchard had died plant with symptoms of root rot problems (Dubrovina & Batista, 2014; Durand & Claassens, 1987).

Location 5

This orchard, located in San Vicente, Guayllabamba parish, Pichincha province, was planted around 40 years ago with Fuerte-Nacional varieties on a 5 ha area (204 trees ha^{-1}). The orchard had a regular topography with a slight slope (5-12%) and a vigorous general appearance, with tree heights ranging from 6 to 12 m. However, tree mortality exceeded 50%. The orchard's productivity was 15 t ha^{-1} (24 kg tree^{-1}), surpassing both the national and provincial averages and yields from other countries like Colombia and Mexico (MAG, 2023; SIAP, 2024).

The soil was classified as Entisols with good drainage and no signs of waterlogging. Four horizons were identified: A (0-15 cm), C1 (15-40 cm), C2 (40-70 cm), and Ab (>70 cm), all with a sandy loam texture ($\bar{x}$: sand 71%, silt 20%, clay 8.5%). The structures were granular in the A horizon and subangular blocks in the A1 and Ab horizons, while the C horizons lacked a defined structure (Figure 8 and Table 4). The root population was distributed throughout the profile, with higher concentrations in the C2 horizon (40-70 cm), likely due to the gravity-fed irrigation system, consistent with root distribution patterns reported by Durand and Claassens (1987), Dixon & Sher (2003), and Schaffer et al (2015). The soil's physical characteristics were ideal for avocado cultivation, as there were no impermeable layers hindering root growth (Shaffer, 2006; Crowley, 2007; Shaffer et al., 2015; Grunennvaldt, 2022), and the moderate annual precipitation (750 mm) minimized risks of hypoxia, waterlogging, and *P. cinnamomi*. However, low clay (5-13%) and organic matter (0.38-1.25%) content could reduce soil fertility due to a low cation exchange capacity, which could be improved through the addition of organic matter and green fertilizers (Sotelo-Nava et al., 2017; Grunennvaldt, 2022). The recorded salinity ($\bar{x}$: 0.04 mS cm^{-1}) was below the threshold for yield decline (0.75 mS cm^{-1}) (Acosta-Rangel et al., 2019).

Figure 8

A. Orchard of Fuerte-Nacional varieties, planted 40 years ago, terrain with a slight slope, B. Percentage of tree mortality greater than 50% and C. effective depth >100 cm with abundant presence of roots at depths ≈70 cm. Province of Pichincha, Quito canton, Guayllabamba parish

Location 6

This orchard, located in Los Andes, Patate canton, Tungurahua province, featured Hass-Nacional variety trees planted 6 years ago in a 5 ha area (400 trees ha^{-1}) with tree heights around 4 meters. The orchard showed medium vigor, with 13% tree mortality and some visible wilting (≈5%). Its yield of 4.85 t ha^{-1} (13.28 kg $tree^{-1}$) was below the provincial (5.31 t ha^{-1}), national (6.11 t ha^{-1}), and international averages (10.41-15.00 t ha^{-1}) (MAG, 2023; SIAP, 2024).

Figure 9.

A. Hass-National Orchard planted 6 years ago, terrain with a slight slope, B. Mortality of plants scattered in the orchard (≈13%) (Google Earth, 08-13-2023) . Province of Tungurahua, Patate canton, Los Andes parish.

The soil was classified as Mollisols, with good drainage and no signs of rising water tables. The effective depth for root growth was 55 cm, comprising two surface horizons: A1 (0-15 cm) and A2 (15-55 cm), both with granular and subangular block structures. The Bt horizon (>55 cm) had strong compaction and no roots, and was not considered part of the effective root zone. This layer contains iron oxide, which can form aggregates by attracting clays and organic matter (Schaetzl and Anderson, 2005). The limited depth for root growth in this soil was a factor in the orchard's productivity, as avocado roots typically develop 80% of their mass between 60 and 150 cm deep (Dixon & Sher, 2003; Crowley, 2007).

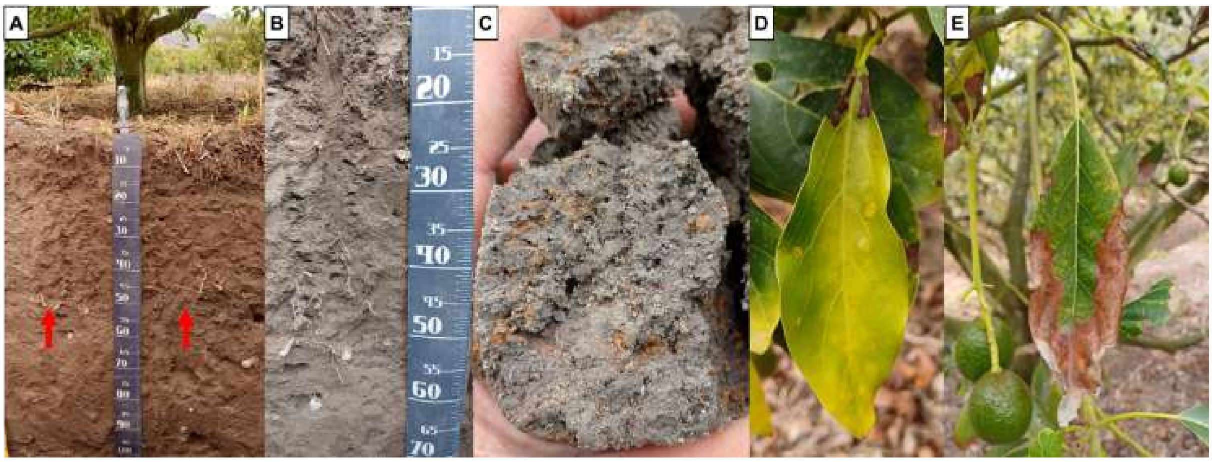
The average soil pH was 7.69, increasing to 7.99 in the Bt horizon, which exceeded the optimal range for Mexican-type rootstocks (6.5) and could contribute to symptoms of iron chlorosis (Kourgialas & Dokou, 2021).

Electrical conductivity (0.08–0.11 mS cm^{-1}) was below the threshold for saline soils, but nutritional deficiencies might have been causing leaf damage (Oster et al., 2007). Organic matter content was 2.42%, within the optimal range, and was higher in the A horizon due to constant fertilization with chicken manure (Selladurai & Awachare, 2020).

Given the low rainfall (650 mm) in the area, the probability of poor drainage is low. However, soil improvement measures such as deep subsoiling, organic matter addition, and green fertilizers could enhance aeration and increase effective root depth (Crowley, 2007; Grunennvaldt, 2022). The use of modern rootstocks tolerant to alkaline-saline conditions, along with pH correction methods like acidifying fertilizers and sulfur application, could also improve soil conditions (Ben-Ya'acov & Michelson, 1995; Wolstenholme, 2003; Barrientos-Priego, 2017; Bender & Faber, 1999).

Figure 10.

A. Hass-Nacional orchard planted 6 years ago, terrain with a slight slope, B. Mortality of plants scattered in the orchard (≈13%). Province of Tungurahua, Patate canton, Los Andes parish.



Location 7

This orchard, located in the coastal region of Santa Elena province, Ecuador, in the El Azúcar locality, spans 60 hectares (416 trees ha^{-1}). It consists of 4-year-old Hass avocado trees grafted onto Zutano rootstock, which are approximately 6 meters high. The yield recorded was 7 t ha^{-1} (11.20 kg $tree^{-1}$), ranking seventh in the study, lower than other orchards such as those in San Joaquín (15 kg $tree^{-1}$) and the Ecuadorian coastal region (11.82 t ha^{-1}), but higher than the national average (6.11 t ha^{-1}) (MAG, 2023). Previous studies in Spain and Australia reported lower yields for Zutano as a rootstock, especially in non-optimal soil conditions (Guirado et al., 2015; Le Lagadec et al., 2011).

The orchard's soil was planted in mounds to address restrictive conditions, such as low depth and poor drainage. Mounds, similar to those used in areas prone to flooding (Schaffer, 2006), were used to improve aeration and reduce risks from soil waterlogging and pathogenic fungi (Pillsbury & Huberty, 1944). However, the orchard showed poor conditions, with tree mortality (≈15%) and reduced vigor, likely due to the rootstock and soil limitations. Zutano has been identified as highly susceptible to waterlogging and root rot caused by *Phytophthora cinnamomi,* a factor contributing to tree mortality in this orchard (Fassio et al., 2011; Schaffer et al., 2015; Gastañadui et al., 2021).

Figure 11

A. Orchard of Hass-Zutano varieties, planted on high mounds, 4 years old, B. Basal resprouting of the rootstock section (serpes). Province and canton of Santa Elena, Colonche parish, El Azucar.

The soil was classified as Vertisol, with poor drainage, limited depth (15 cm), and a compact structure. It consisted of a silty loam A horizon and clay-textured C horizons. These physical limitations and the high clay content (90%) reduce root growth and contribute to poor drainage, conditions that are unfavorable for avocado cultivation (Schaetzl & Anderson, 2005; Dubrovina & Batista, 2014). The soil's compact nature, poor aeration, and high clay content exacerbate water retention, leading to hypoxic conditions, which are detrimental to avocado roots and predispose them to diseases like root rot (Schaffer, 2006; Bonomelli et al., 2019).

Figure 12

A. Soil profile visualized using a pit, with 3 well-defined horizons and a low effective depth of 15 cm, horizon A (red arrow), B. Abundant presence of roots in the horizon A-effective depth, C. High content of clays, plastic soil, C horizon, D. Deep and long cracks caused by possible argiliturbation processes, E. Reaction of an HCl solution with carbonates present in the C horizons. Province and canton of Santa Elena, Colonche parish, El Azúcar locality.

Moreover, the soil's pH (8.49) and high electrical conductivity (1.03 to 2.74 mS cm^{-1}) indicate salinity and alkalinity, further hindering nutrient absorption and tree development (Kourgialas & Dokou, 2021; Acosta-Rangel et al., 2019). The soil's low organic matter content (0.91%) also contributes to its poor fertility (Castro et al., 2009).

In conclusion, the orchard's poor performance can be attributed to the combination of unsuitable soil conditions, such as limited depth, poor drainage, and high salinity, along with the susceptibility of Zutano rootstock to waterlogging and *P. cinnamomi* (Menge et al., 1999; Shaffer et al., 2015).

The presence of excessive clay, compaction, and alkaline conditions makes it difficult for avocado trees to thrive, limiting growth and yields.

Conclusions

The use of sexually propagated Nacional or Criollo rootstock (Mexican breed) is common in the mountains of Ecuador, but it overlooks soil variability and challenges like alkaline pH and drainage problems. The Zutano variety was later used as rootstock in coastal Ecuador's clay soils, without considering its limitations, such as excessive vigor, cold climate adaptation, and susceptibility to root diseases. It is essential to study and select native and imported rootstocks, propagated both sexually and asexually, based on soil characteristics, compatibility with commercial varieties, and local climate. In areas with mild soil restrictions, conditioning efforts are necessary, which will raise costs but are vital for proper avocado cultivation. Commercial orchards should avoid being planted in areas with unfavorable soil and climate conditions, such as shallow (<40 cm) or clayey soils with poor structure and drainage. Using pits before planting orchards is mandatory, as they help select suitable land with the right physicochemical properties and identify corrective actions and their associated costs.

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