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Soil properties associated with West-Indian avocado decline in the agroforestry systems of Montes de María, Colombia

Propiedades del suelo asociadas al declive del aguacate antillano en los sistemas agroforestales de Montes de María, Colombia

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Decline of avocado trees in orchards located in the municipality of Carmen de Bolivar (Colombia).

Photo: O. Burbano-Figueroa

ABSTRACT

The Montes de María (MM) region, a major producer of West Indian avocados in Colombia, has experienced a significant decline in avocado production over the past two decades. This decline has been linked to several biotic stressors, including *Phytophthora cinnamomi* Rands, termites, and ambrosia beetles, though these factors alone do not fully explain the spatial variability of tree decline across the region. This study aimed to assess the role of soil chemical and physical properties in exacerbating avocado decline in MM. Soil samples were collected from 33 avocado orchards with varying levels of decline. Principal Component Factor (PCF) analysis was used to identify the soil parameters most strongly associated with avocado decline. The analysis identified five principal components, accounting for 76.8% of the total variance in soil properties. Among these, PCF1, strongly associated with Ca, pH, and effective cation exchange capacity (ECEC), had a significant positive correlation with shoot dieback (SDB), indicating that avocado trees in soils with higher Ca and pH levels are more prone to decline, likely due to induced iron chlorosis under alkaline conditions. In contrast, PCF5, associated with phosphorus (P) and organic matter (OM), showed a strong negative correlation with SDB, suggesting that higher levels of P and OM may help reduce disease severity and slow its progression. These findings underscore the

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importance of soil management in mitigating avocado decline and highlight the need for integrated strategies to address both biotic and abiotic stressors.

Additional key words: *Persea americana* Mill.; soil chemical-physical properties; Colombian Caribbean; *Phytophthora cinnamomi* Rands; shoot dieback.

RESUMEN

La región de Montes de María (MM), un importante productor de aguacates antillanos en Colombia, ha experimentado una disminución significativa en la producción de aguacates en las últimas dos décadas. Esta disminución se ha relacionado con varios factores de estrés bióticos, incluidos *Phytophthora cinnamomi* Rands, termitas y escarabajos ambrosiales. Sin embargo, estos factores por sí solos no explican completamente la variabilidad espacial del deterioro de los árboles observada en la región. Este estudio tuvo como objetivo evaluar el papel de las propiedades químicas y físicas del suelo en la exacerbación del declive del aguacate en MM. Se recolectaron muestras de suelo de 33 fincas de aguacate con diferentes niveles de declive. Se utilizó el análisis de factores de componentes principales (FCP) para identificar los parámetros del suelo más fuertemente asociados con el declive del aguacate. El análisis identificó cinco componentes principales, que explican el 76.8% de la varianza total en las propiedades del suelo. Entre estos, el PCF1, fuertemente asociado con Ca, pH y capacidad de intercambio catiónico efectivo (CICE), tuvo una correlación positiva significativa con la muerte descendente de ramas (MDR), lo que indica que los árboles de aguacate en suelos con niveles más altos de Ca y pH son más propensos al declive, probablemente debido a la clorosis férrica inducida en condiciones alcalinas. En contraste, el PCF5, asociado con P y materia orgánica, mostró una fuerte correlación negativa con MDR, lo que sugiere que niveles más altos de P y OM pueden ayudar a reducir la gravedad de la enfermedad y ralentizar su progresión. Estos hallazgos subrayan la importancia del manejo del suelo para mitigar el declive del aguacate y resaltan la necesidad de estrategias integradas para abordar tanto los estresores bióticos como los abióticos.

Palabras clave adicionales: *Persea americana* Mill.; propiedades fisicoquímicas del suelo; Caribe colombiano; *Phytophthora cinnamomi* Rands; muerte descendente de ramas.

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INTRODUCTION

Montes de María (MM), located in the Colombian Caribbean, is one of the largest producers of West Indian (WI) avocados in the country. However, in recent years, the region has experienced a dramatic decline in avocado production. Avocado yields have dropped from 70,000 t in 2004 to 18,000 t by 2022, with avocado acreage shrinking by almost half during the same period (Yabrudy, 2012; MinAgricultura, 2024). This decline has been attributed to multiple biotic stressors, including *Phytophthora cinnamomi* Rands, termites, and ambrosia beetles, all of which are major contributors to avocado tree mortality in the region (Osorio-Almanza *et al*., 2017; Burbano-Figueroa *et al*., 2018; Burbano-Figueroa, 2019). *P. cinnamomi* weakens the trees by damaging their root systems, while termites and ambrosia beetles primarily attack trees already weakened by environmental factors such as drought. The combination of these biotic agents exacerbates tree decline, accelerating mortality and significantly reducing avocado productivity in the region.

The avocado decline observed in MM can be better understood through the lens of the “decline disease spiral” model, introduced by Manion. This model explains that tree mortality is a cumulative process, influenced by three categories of factors: predisposing, inciting, and contributing (Manion, 1991; Sinclair and Hudler, 1988). Predisposing factors, such as the advanced age of trees or unfavorable soil conditions, gradually weaken the trees. Inciting factors, like prolonged drought or pest infestations, trigger acute stress that further compromises tree health. Contributing factors, such as secondary pathogens, exacerbate the situation, creating a spiral of decline that accelerates tree mortality (Das *et al*., 2016; Etzold *et al*., 2019). This framework is particularly relevant to the avocado decline in MM, where the tropical dry forest biome, coupled with increasing climate-related stressors, intensifies tree vulnerability to pests and pathogens.

Our study aimed to explore the relationship between soil properties and the severity of avocado decline in MM. We hypothesized that specific soil physicochemical characteristics may either intensify or alleviate the impact of the disease. To address potential confounding factors, our analysis focused on how variations in soil properties influence the occurrence of symptoms related to losses in vigor and health. By examining these interactions, we seek to provide a comprehensive understanding of the underlying factors contributing to the avocado decline in the MM region. Ultimately, our findings aim to inform management practices that can help mitigate further decline and restore productivity in this key agricultural region.

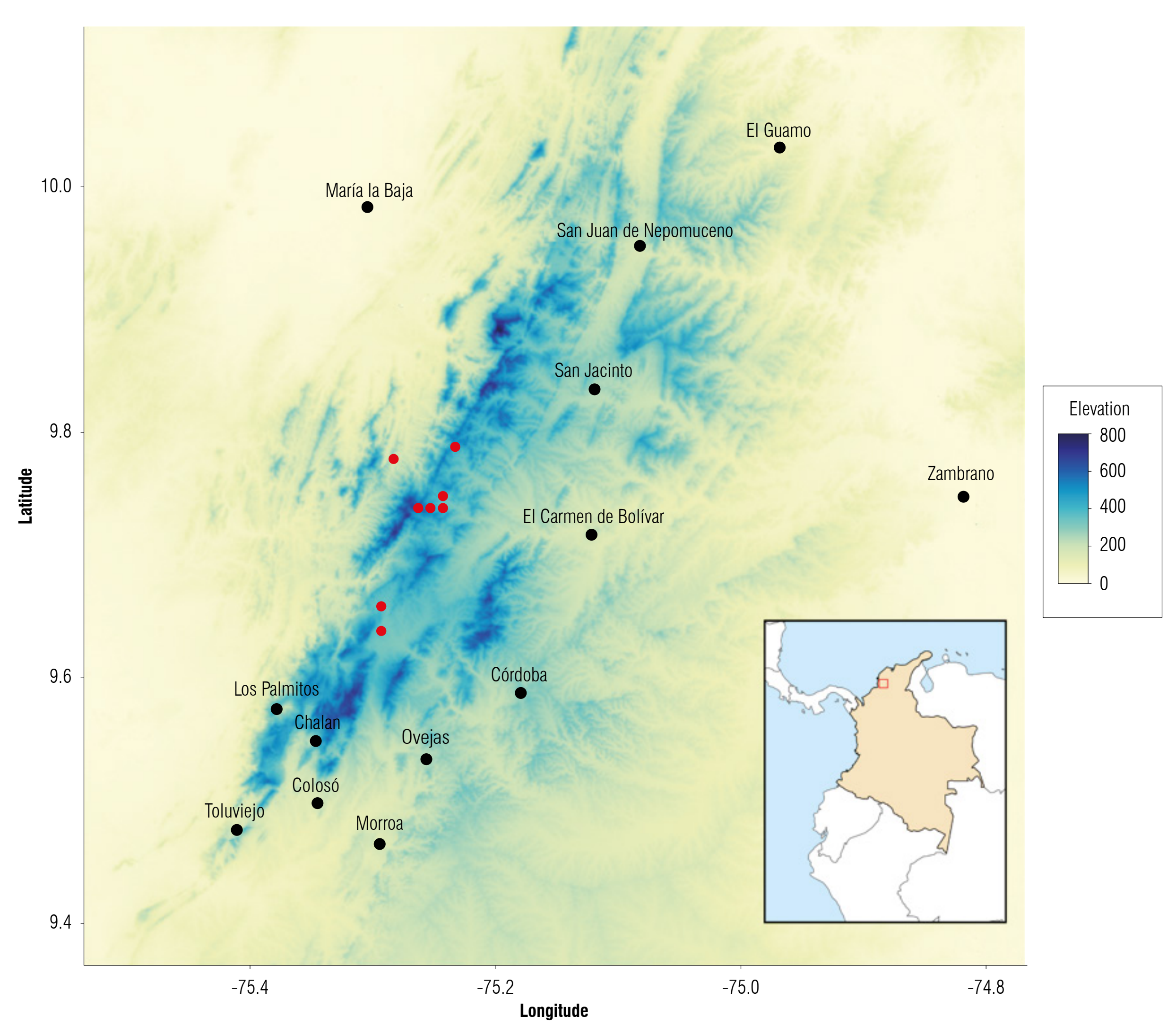

Figure 1. Spatial distribution of sampling sites (red dots) across avocado farms in the Montes de María region, Colombia. Black dots and labels indicate the locations of urban centers within the municipalities of Montes de María (Colombia).

MATERIALS AND METHODS

Site description

This study was conducted in the Montes de María (MM), also known as Serranía de San Jacinto, a low-elevation mountain range located near the Caribbean coast, north of the Colombian Andes. The MM region is the primary avocado-producing area in the Colombian Caribbean, particularly for the West Indian avocado (*Persea americana* var. *americana*). The agricultural landscape in MM is characterized by agroforestry systems where avocado and cacao orchards are frequently intercropped with yam (*Dioscorea* sp.) (Burbano-Figueroa, 2019). These agroforestry systems resemble secondary forests with high trees (>15 m) and old avocado trees that are randomly distributed throughout the landscape. Producers intervene minimally in the crop, primarily acting as gatherers rather than active farmers. In these systems, avocado trees serve multiple purposes, including providing shade for other crops, fruit for consumption, and a secure source of income. Farming practices in MM are typified by non-technified subsistence agricultural economies (Yabrudy, 2012).

The MM region falls within the tropical dry forest biome, characterized by prolonged dry seasons and periodic droughts. This region experiences a tropical savanna climate with dry winters (Aw), influenced by the elevational variations of the MM massif. The area exhibits a bimodal rainfall distribution, with a distinct dry season and a mean annual temperature of 27°C. The geographical range of the farms studied lies between latitudes 9.64° and 9.97° and longitudes -75.31° and -75.15°, with altitudes ranging from 175 to 566 m a.s.l., spanning the departments of Bolivar and Sucre (Fig. 1).

Sample collection

Soil samples were collected from 32 avocado orchards in the MM region between 2013 and 2015. These farms were selected based on the presence of avocado decline symptoms, with the aim of investigating the relationship between soil properties and disease severity. For each farm, six soil samples were collected from different trees, representing a range of avocado decline symptoms. The sampling procedure involved collecting soil from two specific locations around each tree: the middle and the outer edge (border) of the root zone. The middle refers to the area near the trunk, where root density is typically higher, and the border represents the outer extent of the root system, near the canopy edge. This approach ensured that soil conditions influencing tree health were captured accurately.

Soil samples were collected at a depth of 0-20 cm from both the middle and the border of the root zone. These samples were placed in plastic bags, properly labeled, and stored under cool conditions (10-12°C) during transport to the site of analysis. A range of chemical and physical analyses were performed on these soil samples (Tab.1), including pH, calcium content, phosphorus levels, organic matter, and texture (Tab. 1S; see supplementary tables).

For hydraulic conductivity measurements, specific soil samples were collected separately using metal rings to preserve the soil structure. These intact soil cores were carefully extracted from the field to minimize disturbance. The samples were then transported to the site of analysis while still inside the metal rings to maintain the integrity of the soil structure. In the laboratory, hydraulic conductivity was assessed using a constant-head permeameter, a method that measures the soil's ability to transmit water when it is saturated. This technique provides key insights about water movement through the soil, which is important for understanding its impact on tree health, especially in relation to root diseases like avocado decline.

In addition to soil analysis, the severity and incidence of avocado decline were recorded for each farm. The study determined the prevailing level of disease using the highest recorded data on the incidence and severity of avocado decline from at least three different transects per farm.

Assessment of avocado decline

The severity of avocado decline on each farm was visually estimated along 100-m transects using a progressive symptoms scale. These transects were placed in areas reported by farm owners as having the highest levels of tree decline. Soil samples were collected from the same areas where decline symptoms were observed. The transect observation method was chosen due to the random distribution of trees on highly rugged terrain.

Table 1. Description of disease parameters and soil properties used in this study.

Variables	Units	Description	Determination method
Severity index	Dimensionless	Severity index estimated from disease severity records	Visual estimation
SDB	Frequency (0 to 1)	Shot dieback occurrence	Visual estimation
pH	Dimensionless		Potentiometer
EC	dS m^{-1}	Electrical conductivity	Conductivity meter soil:water 1:5
OM	%	Organic matter	Walkey and Black
P	mg kg^{-1}	Available phosphorus (P)	Bray II
S	mg kg^{-1}	Available sulfur (S)	Calcium phosphate monobasic
Ca	$cmol_{(+)}$ kg^{-1}	Exchangeable calcium (Ca)	Ammonium acetate 1N pH 7.0
Mg	$cmol_{(+)}$ kg^{-1}	Exchangeable magnesium (Mg)	Ammonium acetate 1N pH 7.0
K	$cmol_{(+)}$ kg^{-1}	Exchangeable potassium (K)	Ammonium acetate 1N pH 7.0
Na	$cmol_{(+)}$ kg^{-1}	Exchangeable sodium (Na)	Ammonium acetate 1N pH 7.0
ECEC	$cmol_{(+)}$ kg^{-1}	Effective cation exchange capacity	Total amount of exchangeable cations
B	mg kg^{-1}	Available boron (B)	Calcium phosphate monobasic
Cu	mg kg^{-1}	Available copper (Cu)	Modified Olsen
Fe	mg kg^{-1}	Available iron (Fe)	Modified Olsen
Mn	mg kg^{-1}	Available manganese (Mn)	Modified Olsen
Zn	mg kg^{-1}	Available zinc (Zn)	Modified Olsen
Clay	%	Texture	Bouyoucos hydrometer method
Silt	%		
Sand	%		
HC	cm h^{-1}	Hydraulic conductivity	Constant-head permeameter

The severity scale included three levels:

1. Chlorotic or pale leaves
2. Necrotic margins on leaves, and
3. Small branches dying back at the top of the tree or shoot dieback (SDB).

The severity index (SI) was calculated by summing the frequencies of each symptom level, with scores ranging from 1 to 3, and assigning 3 to the most severe level (SDB).

Exploratory data analysis

Correlations between 19 soil properties and the occurrences of SI and SDB were estimated using Pearson's product-moment correlation coefficients. SDB occurrence was selected for further analysis over SI because it showed less variation related to visual estimation by humans (based on field assistant calibration before data collection) and was strongly correlated with overall decline severity. The data revealed a high correlation (r^2 = 0.86) between SDB and SI. A previous study in MM with a larger sample size showed a similar trend (Osorio-Almanza *et al*., 2017).

The relationships between soil parameters and SDB occurrence were analyzed using principal component factor (PCF) analysis with Varimax rotation. Loading values with an absolute value of 0.35 or higher were considered significant for intercorrelation among variables within a principal component. We chose a threshold of 0.35 for the factor loadings in our PCF analysis to strike a balance between statistical rigor and biological relevance. A loading of 0.35 explains roughly 12% of the variance, which is meaningful in ecological studies where variability is high due to complex environmental interactions. In similar research contexts, thresholds ranging from 0.30 to 0.40 have been widely used to capture key associations without being overly restrictive (Hair *et al*., 1998; Tabachnick and Fidell, 2013).

Given the complexity of soil-plant-pathogen interactions, a more stringent threshold could have excluded important variables from our analysis, potentially omitting meaningful insights into avocado decline. This value allows us to identify relevant soil parameters, such as Ca and pH, that contribute to disease dynamics, while ensuring that our findings remain interpretable within the scope of the study (Pituch and Stevens, 2016).

Soil properties are known to influence the interactions between pathogens, pests, and their hosts, potentially explaining the local variations in tree decline and mortality (Sterne *et al*., 1977; Sterne *et al*., 1978; Larkin, 2015; Ababa, 2024; Cao *et al*., 2024; Chaudhary *et al*., 2024). However, the extensive variability in soil properties between locations complicates our understanding of their effects on soil-borne diseases and their specific interrelations. To address this complexity, PCF analysis is a valuable tool for identifying general trends and correlations between biologically relevant soil properties, distilling them into a smaller number of factor components (Sano *et al*., 2015; Lima *et al*., 2017; Klimkowicz-Pawlas *et al*., 2019; Buss *et al*., 2019; Vaca *et al*., 2023; Yadav *et al*., 2023). By applying Varimax rotation, these components can be orthogonally transformed to align the principal components with observed data, enhancing the interpretation of results by maximizing the correlation between underlying latent constructs and observed variables (Vasu *et al*., 2016).

PCF analysis has proven effective in understanding soil conditions related to plant diseases, both at the experimental-field level and the farm level (Khaledian *et al*., 2016; Li *et al*., 2017; Naseri and Tabande, 2017; Rangel-Peraza *et al*., 2017; Arcoverde *et al*., 2019; Buss *et al*., 2019; Indarto *et al*., 2022). It is also widely used to identify underlying soil parameter structures that define soil quality (Mukherjee and Lal, 2014; Vasu *et al*., 2016) and to assess the impact of land-use changes on soil health (Cherubin *et al*., 2016; Raiesi, 2017).

Predictive models for explaining the effect of soil parameters over SDB

To determine the relationship between soil parameters and shoot dieback (SDB) severity, we conducted a stepwise multiple regression analysis. Stepwise selection, an iterative method, was utilized to select the most important predictors. The analysis started with all variables, and the best subset of variables was chosen by minimizing the Akaike Information Criterion (AIC), which balances model fit and complexity. The final model was established after eliminating insignificant variables based on their AIC values. This model aims to identify the most significant soil properties contributing to SDB. The resulting regression coefficients serve to quantify the impact of each variable on SDB.

In addition to stepwise regression, we used ridge regression to address multicollinearity among soil variables, which can lead to unstable coefficient estimates in ordinary least squares regression. Ridge regression incorporates a penalty to the regression coefficients, shrinking them toward zero but never completely eliminating them. This method allows for the inclusion of all predictor variables, regardless of multicollinearity, and provides a more robust model for predicting SDB severity. Before applying ridge regression, all soil parameters and the SDB index were standardized to have a mean of zero and a standard deviation of one. The optimal penalty term (lambda) for the ridge regression model was determined through cross-validation, ensuring the best fit for the data. The final model included coefficients for all soil parameters, providing insights into their relative influence on SDB severity while accounting for the presence of multicollinearity.

Both models were implemented in R using the MASS package for stepwise regression and the glmnet package for ridge regression. Model performance was assessed by calculating the mean squared error (MSE), and model coefficients were interpreted in the context of their biological relevance to avocado decline in the MM region.

RESULTS

The analysis of soil samples from 33 avocado farms in the MM region revealed a wide distribution of avocado decline, which paralleled significant variations in soil properties (Tab. 2). Notably, properties such as calcium (Ca) and pH were related to higher values of avocado decline, indicating their potential role in influencing tree health. For example, farms with soil Ca levels above 20 $cmol_{(+)}$ kg^{-1} and pH values above 7.0 exhibited avocado decline severity indices that were, on average, 50% higher compared to farms with lower Ca and pH levels.

Diversity of soils across the Montes de María

The avocado farms in the MM region exhibited wide variability in soil texture, ranging from heavy clay to lighter loam textures. Several farms presented intermediate textures, such as clay loam and sandy clay loam. Figure 2 illustrates these variations using a soil texture triangle, showing that the majority of soil samples were classified as clay and clay loam.

The pH levels of the soils also varied widely, spanning from moderately acidic (5.82) to moderately alkaline (8.19). This broad pH spectrum underscores

Table 2. Soil properties and disease parameters in avocado orchards from the Montes de María region (Colombia).

Variables*	Units	Mean	Standard deviation	Range	
				Lower bound	Upper bound
Altitud	m a.s.l.	405	105	175	566
Severity index	Dimensionless	1.61	1.22	0.00	4.90
SDB	Frequency	0.32	0.26	0.00	1.00
pH	Dimensionless	6.76	0.56	5.82	8.19
EC	dS m^{-1}	0.36	0.15	0.15	0.77
OM	%	3.35	0.82	2.02	5.01
P	mg kg^{-1}	11.19	11.71	2.40	53.94
S	mg kg^{-1}	4.04	1.35	2.29	7.50
Ca	$cmol_{(+)}$ kg^{-1}	22.26	8.29	11.66	43.80
Mg	$cmol_{(+)}$ kg^{-1}	5.95	3.27	0.77	12.76
K	$cmol_{(+)}$ kg^{-1}	0.64	0.35	0.23	1.71
Na	$cmol_{(+)}$ kg^{-1}	0.12	0.05	0.06	0.31
ECEC	$cmol_{(+)}$ kg^{-1}	28.86	8.61	15.25	46.68
B	mg kg^{-1}	0.32	0.14	0.09	0.58
Cu	mg kg^{-1}	2.75	0.69	1.40	4.45
Fe	mg kg^{-1}	19.14	7.34	8.28	39.32
Mn	mg kg^{-1}	2.71	1.38	1.00	7.02
Zn	mg kg^{-1}	1.01	0.24	0.57	1.58
Clay	%	39.07	9.19	18.40	56.50
Silt	%	29.11	4.98	17.07	37.73
Sand	%	31.88	10.26	18.47	62.93
HC	cm h^{-1}	2.73	2.80	0.12	11.81

m a.s.l., meters above sea level; SDB, shoot dieback; pH, soil acidity/alkalinity, EC, electrical conductivity; OM, organic matter; P, phosphorus; S, sulfur; Ca, calcium; Mg, magnesium; K, potassium; Na, sodium; ECEC, effective cation exchange capacity; B, boron; Cu, copper; Fe, iron; Mn, manganese; Zn, zinc; HC, hydraulic conductivity. See supplementary data for further details.

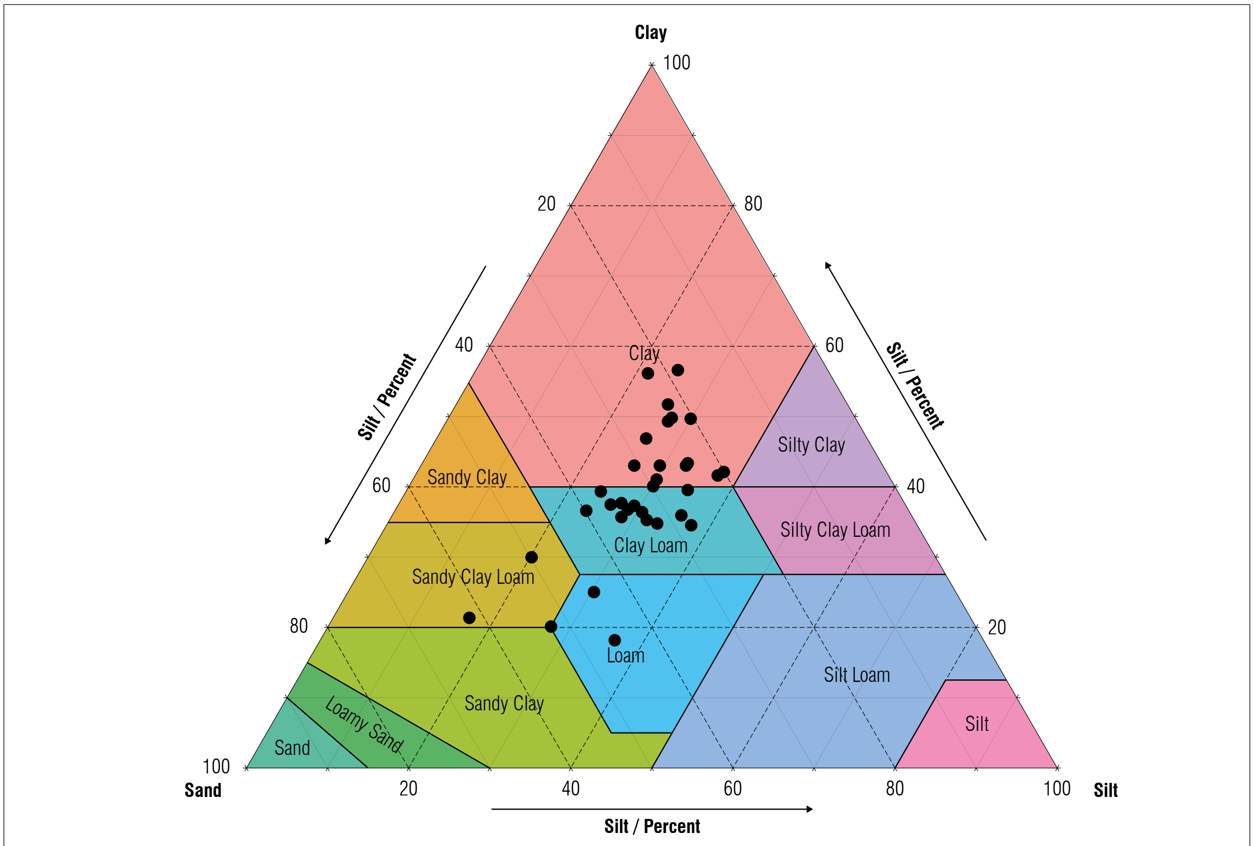

Figure 2. Soil types of avocado farms at Montes de María, Colombia.

the diverse soil conditions across the sampled farms. In addition to pH, the analysis revealed significant variability in the levels of calcium (Ca) and other exchangeable cations, measured by the effective cation exchange capacity (ECEC). The calcium concentrations ranged from 2.29 to 43.80 $cmol_{(+)}$ kg^{-1}, while the ECEC values varied from 11.66 to 46.68 $cmol_{(+)}$ kg^{-1}.

Multivariate approaches to identifying key soil factors influencing shoot dieback

Given the limitations of linear regression in handling multidimensional and correlated datasets, we turned to alternative multivariate techniques, such as principal component factor (PCF) analysis and hierarchical clustering, to better identify the key soil parameters contributing to avocado decline. By applying these complementary methods, we were able to gain deeper insights into the complex relationships between soil properties and avocado decline in the MM region. Together, these techniques provided a more comprehensive understanding of the factors driving disease severity, highlighting the soil parameters most strongly linked to avocado tree health.

PCF analysis, a dimensionality reduction technique, was used to simplify the dataset by identifying the key soil variables that account for the most variance within the system. This approach is particularly useful in ecological studies where numerous interacting variables may obscure relationships. By grouping related variables into principal components, PCF analysis allows us to pinpoint the soil properties that are most strongly associated with avocado decline (Fabrigar and Wegener, 2012). The five principal components identified in our analysis explained 76.81% of the total variance, which is considered substantial in ecological studies, allowing us to focus on the most relevant factors (Tab. 3).

Among these, PCF1, primarily associated with calcium (Ca) and pH, demonstrated a significant positive correlation with shoot dieback (SDB), with a loading value of 0.42. This suggests that higher Ca levels and alkaline soils may contribute to increased avocado decline severity. In contrast, PCF5, which was associated with phosphorus (P), exhibited a notable negative correlation with SDB, with a loading value of -0.62. This indicates that elevated phosphorus levels may play a protective role against shoot dieback, potentially alleviating the impact of the disease. While PCF1 and PCF5 were most strongly correlated with SDB, the remaining components (PCF2, PCF3, and PCF4) displayed weak or insignificant relationships with avocado decline in this analysis.

In addition to the PCF analysis, we used hierarchical clustering to group the soil variables based on their similarities and contributions to avocado decline. Hierarchical clustering generates a dendrogram, a tree-like diagram that visually represents how variables are grouped together step by step, either merging or dividing, based on their proximity in the dataset (Everitt *et al*., 2011). As shown in figure 3, the clustering process identified a group of soil properties, including Ca, pH, and effective cation exchange capacity (ECEC), which are positively correlated with shoot dieback (SDB). This clustering pattern aligns with the results from PCF1, reinforcing the strong association between these soil characteristics and avocado decline severity.

While PCF analysis simplifies the complexity of the dataset by grouping soil variables into principal components, hierarchical clustering provides a visual tool for understanding the relationships among these variables. The two methods together provide complementary insights into the key drivers of avocado decline. By using both PCF analysis and hierarchical clustering, we ensured that our results were not biased by any single method and that the identified associations between soil properties and avocado decline were robust and reliable.

Table 3. Principal component factor analysis (varimax rotation) of shoot dieback (SDB) and soil properties.

Variables	Loading values for PCFs				
	1	2	3	4	5
	Ca	S	Na	Clay	P
SDB	0.42	0.08	-0.12	0.11	-0.62
Ca	0.93	-0.07	0.13	-0.16	-0.09
pH	0.92	0.07	-0.12	0.20	-0.04
ECEC	0.84	-0.24	0.39	-0.06	-0.10
EC	0.68	0.58	-0.14	0.14	0.22
B	0.54	0.57	0.22	0.20	0.34
Silt	0.45	-0.45	-0.30	-0.01	-0.29
Mn	-0.46	0.30	0.60	0.41	0.01
K	-0.05	0.36	0.44	0.14	0.51
OM	-0.19	0.60	-0.20	-0.19	0.50
P	0.18	0.13	-0.25	0.14	0.76
Fe	-0.01	-0.58	0.08	-0.32	0.28
Mg	-0.05	-0.44	0.63	0.24	-0.12
S	-0.11	0.81	0.10	0.04	0.12
HC	0.22	0.63	0.55	0.23	0.00
Na	0.05	0.09	0.84	0.28	-0.28
Zn	0.27	0.07	0.78	-0.24	0.35
Sand	-0.18	0.22	0.22	0.87	0.12
Cu	-0.15	-0.05	-0.07	-0.77	0.00
Clay	-0.05	0.01	-0.06	-0.95	0.03

Different shadings indicate different significant loading values (greater than or equal to the absolute value 0.35): grey, no significant correlation, and intense dark color (black) loading values near 1.

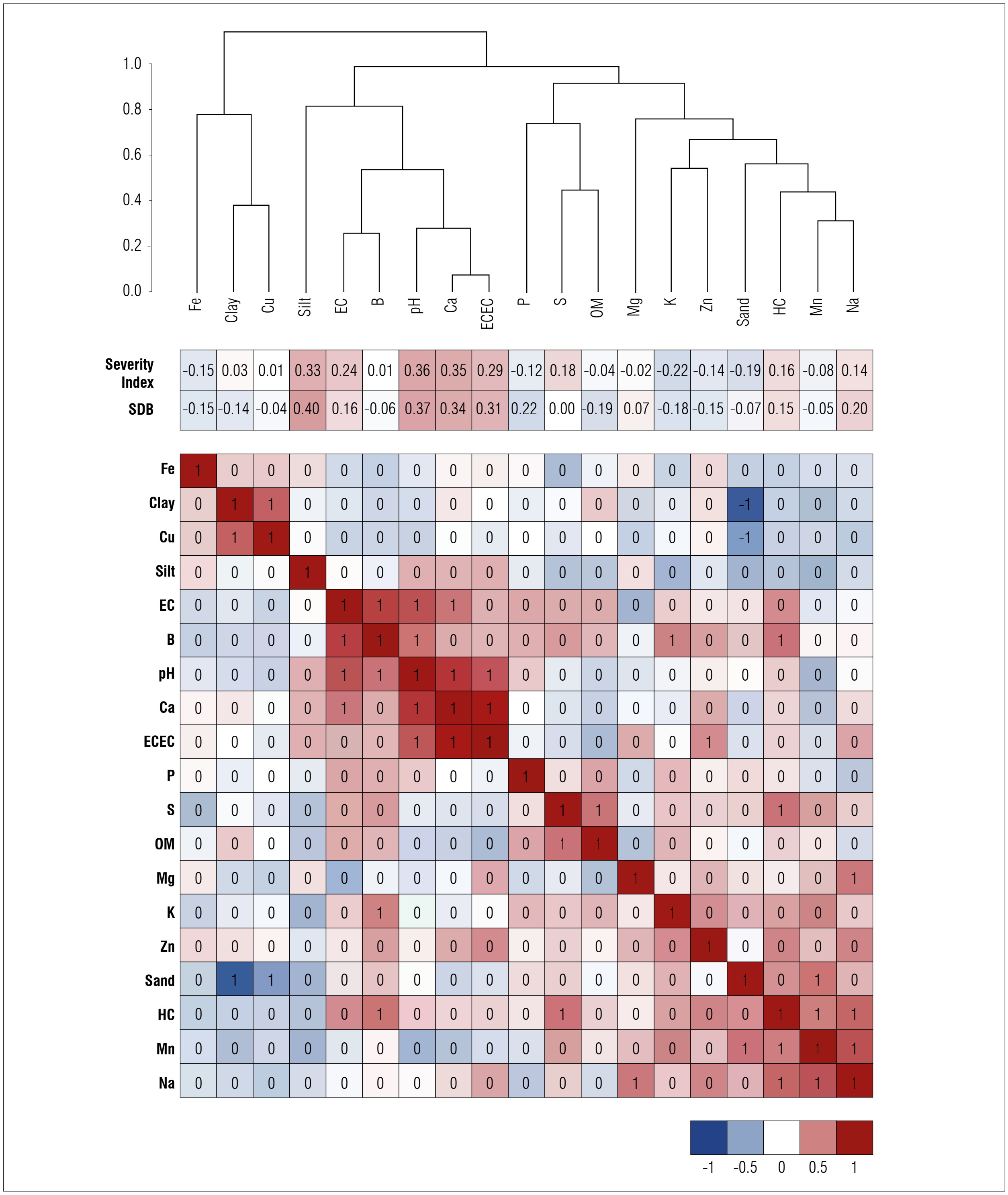

Figure 3. **Correlations between soil properties of Montes de María orchards. Hierarchical clustering revealed a strong cluster comprising pH, calcium (Ca), and effective cation exchange capacity (ECEC). This cluster is significantly associated with higher values of avocado decline, as indicated by the Severity Index and Shoot Dieback (SDB) correlations shown on the upper side of the figure.**

Assessment of predictive models for explaining the effect of soil parameters on SDB

To assess the relationship between soil parameters and shoot dieback (SDB) severity, both stepwise multiple regression and ridge regression models were applied. The stepwise regression model identified a combination of soil variables that were significantly related to SDB, including potassium (K), phosphorus (P), and silt content. The final model demonstrated a good fit, with an adjusted R^2 of 0.42, indicating that these variables explain 42% of the variation in SDB severity (Tab. 4). This model suggested that potassium and silt content were positively associated with SDB, indicating that higher levels of these factors may contribute to increased dieback severity. Conversely, phosphorus exhibited a negative association with SDB, implying that higher phosphorus levels may mitigate the impact of the disease.

Table 4. Stepwise multiple regression model predicting shoot dieback (SDB) based on soil properties.

Predictor	Estimate	Standard error	*t*-value	*p*-value
Intercept	**-29.178**	**12.665**	**-2.304**	**0.0350***
pH	0.432	0.232	1.862	0.0811
EC	-1.038	0.823	-1.261	0.2252
OM	0.159	0.100	1.592	0.1309
P	-0.010	0.004	-2.310	0.0346*
S	0.095	0.049	1.947	0.0693
Ca	0.153	0.094	1.638	0.1210
Mg	0.146	0.080	1.837	0.0849
K	0.576	0.230	2.500	0.0237*
ECEC	-0.140	0.087	-1.611	0.1268
B	-1.217	0.783	-1.553	0.1399
Cu	0.126	0.091	1.384	0.1854
Zn	-0.501	0.270	-1.856	0.0820
Clay	0.249	0.128	1.951	0.0688
Silt	0.279	0.130	2.142	0.0480*
Sand	0.258	0.125	2.062	0.0559

* $P<0.05$ indicates significance at the 5% level.

In contrast, the ridge regression model, which accounts for multicollinearity by shrinking the regression coefficients of less significant variables, provided a broader perspective by including all soil parameters, reflecting their collective impact on SDB. In this model (Tab. 5), the ridge coefficients showed that pH (estimate: 0.0617) and calcium (estimate: 0.0397) had the highest positive contributions to SDB severity, indicating that higher pH and calcium levels were associated with an increased risk of dieback. These findings are consistent with the earlier discussions about the effect of high pH and calcium in causing nutrient imbalances, particularly iron deficiency, which could exacerbate tree vulnerability. Furthermore, exchangeable cations (ECEC) showed a positive contribution (estimate: 0.0325), reinforcing the notion that soil conditions with high base saturation may negatively impact avocado health in MM. On the other hand, phosphorus (estimate: -0.0365) and organic matter (OM) (estimate: -0.0291) had negative coefficients, corroborating their protective role against SDB, as also noted in the stepwise model (Tab. 5).

Table 5. Ridge regression coefficients for soil parameters and their relationship with shoot dieback (SDB).

Soil parameter	Coefficient estimate*
(Intercept)	0
pH	0.062
EC	0.024
OM	-0.029
P	-0.036
S	-0.008
Ca	0.04
Mg	0.006
K	-0.031
Na	0.018
ECEC	0.032
B	-0.001
Cu	0.007
Fe	-0.022
Mn	-0.02
Zn	-0.043
Clay	-0.029
Silt	0.066
Sand	-0.006
HC	0.034

* These are the coefficient estimates obtained from the ridge regression model. The coefficients indicate the relative contribution of each soil parameter to Shoot Dieback (SDB). Positive values indicate a direct relationship, while negative values suggest an inverse relationship between the soil parameter and SDB.

While the stepwise regression model focused on identifying key variables that independently influence SDB, the ridge regression provided a more comprehensive view of how multiple factors, even those with smaller individual effects, interact to contribute to the decline. The consistency between the two models regarding the protective role of phosphorus, and the importance of soil pH and calcium, highlights these as critical areas for future management strategies in mitigating avocado decline. The divergence in other variables, such as the role of organic matter and exchangeable cations, underscores the complexity of soil-plant-pathogen interactions in avocado orchards and points to the need for multifaceted approaches in addressing tree decline in MM.

Principal component factor (PCF) analysis and hierarchical clustering reveal soil parameters contributing to avocado decline

The findings from the PCF analysis, particularly PCF1 (dominated by calcium, pH, and exchangeable cations), are further validated by clustering analysis and the ridge regression model, reinforcing the significance of these soil parameters in avocado decline. Clustering analysis grouped farms with high pH and calcium levels, which consistently correlated with higher SDB severity, a pattern also highlighted by PCF1. Similarly, ridge regression identified pH and calcium as significant contributors to SDB severity, aligning with the results from the PCF analysis. This convergence of independent analytical methods underscores the robustness of PCF1 in explaining the key drivers of avocado decline in the Montes de María region.

Furthermore, PCF5, primarily associated with phosphorus (P) and organic matter (OM), also emerged as a significant factor across multiple models. Both the PCF analysis and the stepwise regression model revealed that phosphorus played a protective role, with a negative correlation to SDB severity. This consistency across methods strengthens the case for phosphorus and organic matter as crucial elements in mitigating tree vulnerability. The identification of PCF1 and PCF5 as significant factors by different analytical techniques highlights their importance in explaining avocado decline, providing strong evidence of the role soil properties play in the disease's progression.

DISCUSSION

This study aimed to identify the soil chemical and physical properties associated with the growing decline of West Indian avocados in the Montes de María region. While previous research has suggested various biotic stressors as potential contributors to this decline, our focus was on understanding the role of environmental factors, particularly soil properties, in exacerbating the problem.

The association between PCF1 (represented by Ca, pH, ECEC, and EC) and avocado decline in the Montes de María region likely stems from the influence of soil pH and calcium on iron availability. Avocado trees thrive in soils with a pH range of 5.5 to 6.5, where iron is more readily available for uptake. However, in soils with pH levels above 7, the high calcium content typical of alkaline soils can reduce iron availability, potentially leading to iron deficiency (Schinas and Rowell, 1977; Salazar-García, 1999). This deficiency, known as iron chlorosis, is a well-documented issue in tropical and subtropical avocado orchards, especially in areas with neutral to alkaline soils (Malo, 1976; Schinas and Rowell, 1977).

The relationship between high pH, elevated calcium levels, and reduced iron availability is well established, and the occurrence of iron chlorosis in such conditions is so pronounced that specific measures have been developed to mitigate it. These strategies include the use of iron chelates, siderophores, and other treatments aimed at enhancing iron uptake (Kadman and Lahav, 1982; Gregoriou *et al*., 1983; Granja and Covarrubias, 2018). Although we did not directly measure iron availability in this study, our results indicate that farms with higher pH and calcium levels experienced more severe avocado decline. This suggests a potential link between soil alkalinity, reduced iron availability, and increased vulnerability to pathogens like *P. cinnamomi.*

Interestingly, PCF5, primarily associated with phosphorus (P) and organic matter (OM), was negatively correlated with SDB, indicating a protective role of these soil components. Phosphorus is an essential nutrient for plant growth, and its deficiency can severely impair plant health, making trees more susceptible to environmental stresses and diseases. Adequate levels of phosphorus may strengthen trees against pathogens, particularly in regions like MM, where multiple stress factors converge. Organic matter, on the other hand, plays a vital role in enhancing soil fertility and improving overall soil health. Soils rich in organic matter tend to have better structure, water retention, and nutrient availability, all of which contribute to tree resilience.

In the context of avocado decline, organic matter may help suppress the activity of *P. cinnamomi,* as previous studies have shown that soils with higher organic matter tend to be more suppressive to pathogens (Broadbent and Baker, 1974). The balance of soil nutrients, such as phosphorus and organic matter, appears to play a critical role in reducing the impact of *P. cinnamomi* and mitigating avocado decline.

In addition to PCF analysis, regression models were employed to further explore the relationship between soil properties and avocado decline. Both stepwise multiple regression and ridge regression were used to identify the most influential soil variables. The stepwise model identified variables such as K, P, and silt as significant predictors of SDB. Potassium and silt content were positively associated with SDB, whereas phosphorus showed a negative relationship, reinforcing its protective role against avocado decline.

Ridge regression, which was employed to address potential multicollinearity, confirmed the importance of soil pH and calcium, further emphasizing the role of soil chemistry in influencing tree health. The consistency between PCF1 and the regression models highlights the central role of soil pH, calcium, and other key soil parameters in driving avocado decline. While the regression models provided useful insights, the dimensionality reduction achieved through PCF analysis proved more effective in identifying the dominant factors contributing to avocado decline in MM.

Environmental stressors and the "decline disease spiral" in avocado trees

Our findings align with previous studies that have emphasized the significance of environmental factors in tree decline and mortality (de Toledo *et al*., 2011; Whyte *et al*., 2016; Gazol *et al*., 2018; Scarlett *et al*., 2021). The decline observed in MM can be understood through the lens of the "decline disease spiral" model proposed by Manion (1991). This model describes tree mortality as a progressive and cumulative process, where a series of interacting factors (predisposing, inciting, and contributing), rather than a single stressor, lead to tree decline and eventual death. The process begins with predisposing factors—such as unfavorable soil conditions, advanced tree age, or prolonged nutrient deficiencies—that gradually weaken the tree over time. These underlying vulnerabilities make trees more susceptible to inciting factors, such as prolonged drought, extreme temperatures, or pest infestations (Manion, 1991; Das *et al*., 2016; Etzold *et al*., 2019).

Predisposing factors set the stage for tree vulnerability by weakening the trees before any major inciting events occur (Manion, 1991; Ciesla and Donaubauer, 1994). Avocado trees in MM are often grown in soils with suboptimal pH levels and limited nutrient availability (which are not supplemented by fertilization), which reduces their resilience to further stressors. Over time, such conditions diminish the trees' capacity to absorb essential nutrients, further contributing to their weakened state. The advanced age of many avocado trees in MM adds to their susceptibility, as older trees generally have reduced vigor and greater difficulty in coping with environmental changes.

Inciting factors act as triggers, causing acute stress that worsens the condition of already vulnerable trees (Manion, 1991). In MM, the tropical dry forest biome presents a particularly challenging environment for tree health. Prolonged droughts and extreme temperatures are common in this region, creating conditions where water scarcity becomes a major limiting factor for tree recovery and growth. Poor soil fertility exacerbates these challenges by preventing trees from accessing the nutrients they need to survive prolonged stress events. These inciting factors, when combined with the predisposing vulnerabilities, significantly reduce the trees' ability to withstand environmental pressures, pushing them further into decline. Climate change will exacerbate these inciting factors, intensifying the environmental stress experienced by avocado trees in the MM region. Rising temperatures and more frequent and prolonged droughts are expected to become increasingly common as a result of global climate change. These shifts not only increase water scarcity but also alter soil moisture dynamics, making it more difficult for trees to recover from stress events (Camarero *et al*., 2015; Bauman *et al*., 2022; Hammond *et al*., 2022). As climate-related stressors amplify, they will contribute to a feedback loop of decline, accelerating tree mortality and threatening the sustainability of avocado production in the region.

Once trees are weakened by predisposing and inciting factors, they become more susceptible to opportunistic pathogens and pests (Manion, 1991; Ciesla and Donaubauer, 1994; Oliva *et al*., 2014). In MM, secondary pathogens like *P. cinnamomi* and pests such as termites and ambrosia beetles take advantage of the compromised state of the avocado trees, accelerating their decline. These biotic agents act as amplifiers within the "decline disease spiral," hastening the transition from stressed trees to tree mortality. The compounding effect of multiple stress agents—both biotic and abiotic—creates a scenario where each additional factor increases the tree's vulnerability to further damage (Manion, 1991).

The relevance of the "decline disease spiral" to the MM region lies in its ability to provide a theoretical framework for understanding the complex, long-term process of avocado decline in this ecosystem. The dry tropical forest biome of MM presents unique challenges, where avocado trees are especially vulnerable to climate-induced stressors. The region's pronounced dry season exacerbates water scarcity, compounding the effects of nutrient-poor soils, which increase the likelihood of deficiencies in essential elements like iron and phosphorus. These stressors interact over decades, creating the ideal conditions for the spiral of decline, where weakened trees are further compromised by biotic agents like pests and pathogens.

The multifaceted nature of the avocado decline highlights the need for comprehensive modeling techniques. Predictive models, including those developed through Geographic Information Systems – GIS, can serve as valuable tools to simulate the interactions between environmental factors, soil conditions, and tree health over time. Such models can identify critical thresholds and prioritize areas for intervention, offering a more dynamic approach to managing the decline. These models can provide early warnings of vulnerable regions, allowing stakeholders to take preventive measures before widespread tree mortality occurs. By integrating soil, climate, and pest management strategies, future efforts can better address the long-term challenges posed by the decline disease spiral in MM and work towards the sustainability of avocado production in the region. However, to fully grasp the wide-reaching impact of this process, it is crucial to incorporate modeling and GIS. These tools provide a broader perspective, allowing us to track changes over time and across landscapes, enabling a better understanding of how predisposing, inciting, and contributing factors have interacted over long periods in MM. Without this broader, system-level approach, it is challenging to appreciate the full extent of the long-term avocado decline occurring in this region.

CONCLUSION

In this study, we examined the relationship between soil properties and avocado decline in the Montes de María region, employing several statistical techniques, including Principal Component Factor (PCF) analysis, stepwise regression, and ridge regression, to identify key factors influencing shoot dieback (SDB) severity.

The PCF analysis identified two key components —PCF1 and PCF5—that were consistently associated with SDB across all statistical assessments. PCF1, primarily dominated by calcium (Ca), pH, and exchangeable cations, was positively correlated with SDB, suggesting that alkaline soils with high calcium levels may worsen the severity of avocado decline. Conversely, PCF5, associated with phosphorus, showed a negative correlation with SDB, indicating that higher phosphorus levels could offer protective effects against the disease. Stepwise regression further validated these findings, with variables such as phosphorus and potassium emerging as significant contributors to SDB severity, supporting the roles of both PCF1 and PCF5. While PCF1's importance was further reinforced by clustering and ridge regression analysis, which pointed to the same critical soil parameters, the stepwise model highlighted specific nutrient-related effects that align with our overall findings.

The consistency of these results across multiple statistical approaches underscores the significance of PCF1 and PCF5 in explaining avocado decline in the region. These findings suggest that focusing on managing soil pH, calcium, and phosphorus levels could play a pivotal role in mitigating tree decline and improving the sustainability of avocado production in the tropical dry forests of Montes de María. Our study demonstrates that soil properties, particularly calcium, pH, phosphorus, and organic matter, play a crucial role in the health of avocado orchards in the Montes de María region.

Supplementary materials and data availability

Aggregated farm-level data are accessible via OSF Preprints (https://osf.io/pa8bs/). Complete datasets, including sensitive information such as specific farm names and locations, will be provided upon request, contingent on signing a confidentiality agreement.

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Conflict of interest

The authors declare that they have no potential conflicts of interest. The funders had no role in the design of the study, data analysis, writing of the manuscript, or the decision to publish the results.

Author contributions

O. Burbano-Figueroa and M. Moreno-Morán: conceptualization and design, funding project and administration, field work and data collection, data analysis and interpretation, original draft, writing, editing and translation, methodology, visualization and presentation, and literature review. J. Romero-Ferrer: conceptualization and design, field work and data collection, data analysis and interpretation, writing and editing, methodology, literature review. All authors read and approved the final manuscript.

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Tabla S1. Soil properties and associated severity variables (shoot dieback and severity index) from avocado orchards in Montes de María (Colombia).

Farm ID		ALT	LAT	LON	SDB	Severity index	pH	EC	OM	P	S	Ca	Mg	K	Na	ECEC	B	Cu	Fe	Mn	Zn	Clay	Silt	Sand	HC
9.2	1	330	9.74	-75.24	0.40	1.70	6.82	0.40	4.29	7.33	5.07	14.90	4.16	0.74	0.07	19.86	0.49	2.70	10.67	1.88	0.60	37.00	28.87	33.47	1.62
9.2	2	412	9.74	-75.25	0.00	0.50	7.30	0.44	4.03	53.94	4.96	15.62	3.79	1.21	0.06	20.68	0.50	2.85	15.18	1.55	1.15	36.67	23.53	39.80	2.05
9.2	3	445	9.74	-75.25	0.00	1.00	6.23	0.35	3.37	5.14	5.72	18.98	6.11	0.59	0.10	25.77	0.29	3.25	11.12	2.33	0.80	56.50	24.87	18.47	1.66
9.2	4	533	9.74	-75.25	0.30	2.20	6.67	0.53	5.01	5.76	5.57	15.55	5.21	0.33	0.07	21.16	0.40	1.57	22.88	2.62	0.70	36.67	28.53	34.80	1.18
9.2	5	534	9.74	-75.25	0.30	1.30	6.71	0.37	4.54	42.15	4.19	17.33	4.22	0.59	0.07	22.21	0.36	2.98	15.92	2.17	0.97	38.00	26.53	36.80	4.65
9.2	6	528	9.74	-75.25	0.00	1.20	5.99	0.39	4.90	36.67	5.57	17.20	6.32	0.84	0.09	24.45	0.28	2.75	34.22	3.48	1.17	43.00	26.20	30.80	4.94
9.2	7	504	9.73	-75.25	0.40	2.50	6.38	0.36	3.37	5.17	7.50	13.79	3.33	0.50	0.07	17.69	0.44	3.18	13.33	2.87	1.18	34.67	33.27	32.07	3.29
9.2	8	508	9.73	-75.25	0.20	1.30	6.48	0.41	4.44	15.27	5.06	15.09	3.79	0.52	0.08	19.47	0.36	2.62	15.53	3.05	0.75	35.67	28.53	35.80	1.35
9.2	9	550	9.74	-75.25	0.00	0.10	5.82	0.23	3.68	2.40	4.15	12.84	3.53	0.81	0.10	17.27	0.19	4.45	23.40	3.57	1.24	51.67	26.20	22.13	5.20
9.2	10	441	9.74	-75.25	0.10	0.40	6.41	0.33	3.58	6.87	2.83	17.30	3.63	0.89	0.08	21.90	0.31	3.05	15.08	2.62	0.78	39.33	23.87	36.80	0.22
9.2	11	556	9.74	-75.25	0.50	2.50	6.42	0.19	2.97	4.58	2.29	11.66	3.03	0.46	0.10	15.25	0.14	3.12	17.95	3.86	0.60	40.00	29.93	30.07	1.12
9.2	12	365	9.66	-75.29	0.00	0.00	6.40	0.28	3.75	6.20	2.70	23.35	7.17	0.64	0.12	31.27	0.33	2.24	34.49	2.04	1.44	49.67	27.67	22.67	1.42
9.2	13	341	9.64	-75.29	0.00	0.00	6.87	0.23	2.72	5.76	3.90	22.86	5.78	0.40	0.13	29.16	0.24	2.27	21.33	1.36	1.00	49.67	30.00	20.33	1.74
9.2	14	519	9.74	-75.26	0.20	0.70	6.94	0.47	3.18	16.10	4.21	17.23	9.27	1.71	0.19	28.39	0.52	1.81	11.72	6.15	1.12	25.00	30.40	44.60	5.46
9.2	15	366	9.75	-75.24	0.30	1.10	7.19	0.47	2.92	11.55	4.83	30.86	8.80	0.99	0.16	40.81	0.53	1.92	8.28	3.76	1.16	20.00	27.40	52.60	8.24
9.2	16	400	9.75	-75.24	0.30	1.00	6.74	0.43	3.40	2.76	6.35	22.12	10.58	1.10	0.31	34.11	0.58	1.40	13.38	7.02	1.58	21.67	17.07	62.93	11.81
9.2	17	175	9.78	-75.28	0.30	0.90	6.73	0.18	2.59	5.60	2.76	23.30	12.76	0.36	0.10	36.52	0.20	2.33	27.28	1.80	1.00	34.67	37.33	28.00	0.64
9.2	18	203	9.78	-75.27	0.60	2.90	6.44	0.15	3.01	4.49	2.61	19.89	10.82	0.35	0.12	31.18	0.22	2.82	29.16	2.32	1.00	41.67	37.33	21.00	0.79
9.2	19	442	9.74	-75.25	0.30	1.60	6.71	0.16	2.27	5.66	2.84	22.53	5.69	0.31	0.13	28.65	0.25	3.04	19.37	3.26	1.00	36.33	30.33	33.33	1.20
9.2	20	492	9.79	-75.23	0.40	1.20	6.22	0.35	4.04	10.04	3.99	21.93	0.77	0.45	0.12	23.26	0.16	3.45	15.90	2.47	0.92	43.00	32.67	24.33	1.31
9.2	21	471	9.79	-75.23	0.00	0.10	6.45	0.36	2.98	7.79	3.49	15.18	0.82	0.23	0.10	16.33	0.09	2.05	18.75	2.78	0.57	30.00	20.00	50.00	2.27
9.2	22	401	9.78	-75.23	0.60	2.40	6.60	0.39	4.01	6.44	3.48	19.37	3.47	1.39	0.08	24.30	0.36	2.92	16.02	2.70	1.13	47.00	25.67	27.33	2.18
9.2	23	292	9.78	-75.28	0.40	1.70	6.64	0.27	2.02	5.81	2.64	21.44	10.91	0.36	0.17	32.89	0.20	2.69	16.52	2.06	1.00	36.00	35.67	28.33	0.61
9.2	24	247	9.78	-75.28	0.20	1.10	6.75	0.20	2.13	5.62	2.73	19.61	10.81	0.35	0.16	30.92	0.18	2.20	14.30	2.32	1.00	35.33	31.67	33.00	0.40
9.2	25	367	9.79	-75.29	0.80	2.90	6.94	0.25	2.06	10.13	2.32	19.82	8.77	0.44	0.08	29.11	0.16	2.10	20.41	1.79	0.57	18.40	36.16	45.44	0.45
9.2	26	347	9.66	-75.31	0.40	2.30	7.70	0.63	2.47	23.16	3.32	41.83	2.69	0.77	0.11	45.40	0.44	3.31	27.64	1.31	1.16	41.00	30.07	28.93	1.18
9.2	27	265	9.65	-75.31	1.00	4.90	8.19	0.77	3.56	12.89	4.91	38.21	4.18	0.38	0.17	39.35	0.52	2.63	19.62	1.25	1.06	39.33	34.67	26.00	9.73
9.2	28	366	9.69	-75.27	0.20	1.30	7.97	0.63	3.27	14.65	2.81	43.80	2.31	0.50	0.06	46.68	0.58	3.18	21.04	1.00	1.11	42.00	37.73	19.93	1.47
9.2	29	370	9.7	-75.27	0.70	3.90	6.60	0.20	2.98	4.22	4.50	27.01	8.61	0.59	0.15	36.36	0.24	3.92	15.76	2.31	1.00	56.00	21.67	22.33	3.37
9.2	30	379	9.81	-75.23	0.60	3.10	8.17	0.53	2.85	10.36	3.61	39.25	1.33	0.25	0.08	40.90	0.34	2.03	12.95	1.00	1.00	43.33	32.67	24.00	3.41
9.2	31	341	9.97	-75.15	0.10	0.50	6.69	0.31	3.86	6.70	3.08	28.09	9.59	0.95	0.13	38.76	0.38	3.50	20.06	1.88	1.41	49.33	27.38	23.27	2.22
9.2	32	324	9.97	-75.15	0.30	0.90	6.64	0.17	2.19	3.93	2.84	20.40	6.41	0.43	0.12	27.46	0.19	3.94	39.32	3.33	1.03	37.67	27.33	35.00	0.12