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EDAPHOCLIMATIC FACTORS RELATED TO VULNERABILITY TO MOKO (*Ralstonia solanacearum* race 2) IN MUSACEAE PRODUCTION SYSTEMS IN COLOMBIA

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ABSTRACT

Ralstonia solanacearum race 2, the causal agent of Moko disease, is considered one of the most significant phytosanitary threats to Musaceae production in Colombia and Latin America, given its severe economic impact due to the loss of plantations and the reduced productive capacity of affected areas. This study aimed to map soil vulnerability to Moko disease in Colombia by integrating climatic and edaphic variables, disease surveillance data for existing outbreaks, and information on Musaceae production units nationwide. Climate and soil databases at national and international levels and expert judgment methodology were used for vulnerability analyses. The results show that, considering climatic and edaphic factors, 90.83 % of the territory exhibits areas of high and very high vulnerability. However, when banana and plantain production units are included in the final vulnerability map, this figure drops to 49.91 % of the territory. A vulnerability ranking was obtained based on the potential incidence of Moko disease. Banana-producing departments such as Magdalena, Antioquia, and Valle del Cauca, as well as plantain-producing departments like Meta, Arauca, Casanare, Córdoba, Sucre, and Chocó, showed high and very high vulnerability indices, these are all representative of the main producing areas of both crops at the national level. It was also found that acids soil, with low organic carbon, poor drainage, and high temperatures and rainfall, show high levels of vulnerability to Moko under conditions of the main banana and plantain production areas of Colombia.
Additional keywords: Banana, climate, epidemiology**,** plantain, soil

RESUMEN

Factores edafoclimáticos relacionados con la vulnerabilidad a Moko (*Ralstonia solanacearum* raza 2) en sistemas de producción de musáceas en Colombia.

Ralstonia solanacearum raza 2, el agente causal de la enfermedad del Moko, es considerada una de las amenazas fitosanitarias más importantes para la producción de Musáceas en Colombia y en Latinoamérica, por el fuerte impacto económico al causar la pérdida de las plantaciones y de la capacidad productiva de las áreas afectadas. Se mapeó la vulnerabilidad de los suelos a la enfermedad del Moko en Colombia mediante la integración de variables climáticas, edáficas, de vigilancia sanitaria de focos presentes de la enfermedad y unidades de producción de musáceas a nivel nacional. Para los análisis de vulnerabilidad se utilizaron bases de datos sobre clima y suelo a nivel nacional e internacional, así como la metodología del criterio experto. Se demostró que, al considerar los factores climáticos y edáficos, el 90,83 % del territorio presenta áreas de vulnerabilidad alta y muy alta; mientras que, al incluir las unidades de producción de banano y plátano en el mapa final de vulnerabilidad de las unidades de producción, este valor es 49,91 % del territorio. Se obtuvo un ranking de vulnerabilidad asociado a la posible incidencia de Moko, donde departamentos productores de banano (Magdalena, Antioquia y Valle del Cauca), y de plátano, (Meta, Arauca, Casanare, Córdoba, Sucre y Chocó) presentaron índice de vulnerabilidad alto y muy alto, siendo todos estos representativos de las principales zonas productoras de ambos rubros a nivel nacional. Se encontró que los suelos ácidos, con bajo contenido de materia orgánica, drenaje deficiente, y temperaturas y precipitaciones altas, presentan niveles altos de vulnerabilidad al Moko en las condiciones de las principales zonas productoras de banano y plátano en Colombia.
Palabras clave adicionales: Banano, clima, epidemiología, plátano, suelo

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INTRODUCTION

Ralstonia solanacearum is a pathogen composed of several strains that cause bacterial wilt in Musaceae clones, known as Moko. In

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Colombia, Moko is an ICA-Regulated Non-Quarantine Pest and it is currently present in at least of 90 % of departments of Colombia, affecting different banana clones such as ´Bananito´ or `Lady Finger´ (AA), `Gros Michel´ and `Cavendish banana´ (AAA), `Manzano´ banana (subgroup Silk, AAB); `Hartón´, `Dominico-Hartón´, `Hawaiano´, `Dominico´, `Curare´ plantains (AAB), and `Popocho´ (subgroup Bluggoe, ABB) (ICA, 2021). The importance is related to easy spread over short and long distances, a wide range of hosts, ineffective management strategies, high economic losses, and eradication that involves the elimination of crop areas and periods of up to six months without production. A better understanding of the epidemiological behavior of Moko would allow for the establishment of more efficient health surveillance measures, as well as improving integrated disease management practices (Rodríguez *et al*., 2018).

The pathogen strains have been divided into races, biovars, phylogroups, and sequevars; those that cause the disease are within biovar 1, race 2, phylotype 2 (Guzmán *et al*., 2025). Moko disease in bananas is caused by strains classified as sequevars 6, 24, 41, and 53 within phylotype IIA and sequevars 3, 4, and 25 within phylotype IIB (Rincón *et al*., 2024).

It colonizes the roots and advances toward the corm, pseudostem, leaves, and fruits of the plant, causing external symptoms characteristic of vascular wilt as well as evident damage in the uneven ripening of the fingers in the bunch, colloquially known in Colombia as Maduraviche (Polanco and Rodríguez, 2024). Symptoms can be very diverse, depending on the type of infection (mechanical, insect, or soil), inoculum pressure in the soil, virulence of the bacteria, presence of other pathogens causing mixed infections, tolerance or resistance mechanisms of the plant, predisposing environmental and edaphic conditions, microbial diversity in the soil, among many other factors. However, vascular wilting is evident because the pathogen adheres to xylem walls, secretes extracellular polysaccharides (EPS), and produces enzymes that degrade host tissues, enhancing its systemic spread. These biofilms not only protect the bacteria from host immune responses but also facilitate their upward movement through the vascular system, contributing to characteristic wilt symptoms (Guzmán *et al*., 2025; Chachar *et al*., 2025).

Short-distance dispersal is caused by the movement of contaminated soil, unsterilized tools, machinery, and agricultural implements; however, over long distances, the disease has spread through contaminated planting material, which is the most critical issue to be resolved to prevent the spread of the pathogen to new crop areas. Some studies have sought to generate theoretical models to explain the epidemiological behavior of the pathogen, as well as to advance strategies for disease prevention and management (Grajales and Muñoz, 2021).

The pathogen has long been reported in Colombia and is currently classified as an officially controlled disease by the Colombian Agricultural Institute (ICA); however, management strategies have been inefficient in containing, especially among small producers, unlike in high tech export farms where eradication and management protocols are applied quite efficiently (Polanco y Rodríguez, 2024). Preventive management in pathogen-free areas is essential, as is integrated disease management in areas where the pathogen is present. However, knowledge of the soil and climate factors that favor the pathogen is very important for the proper design of management strategies (Rodríguez *et al*., 2023b).

For this reason, the objective of this work was to determine the levels of vulnerability in lands and production units of musaceae to Moko, through the systematization and analysis of edaphoclimatic variables and available epidemiological information.

MATERIALS AND METHODS

Study Area. The study was conducted in continental Colombia, whose elevation ranges from sea level to over 5000 masl, generating diverse climates and ecosystems and supporting high biodiversity (USGS-EROS, 2018). Annual precipitation varies widely: the Pacific coast exceeds 3000 mm on average, reaching up to 10 000 mm in areas like Chocó, while the Andean region receives moderate rainfall (1500-3000 mm), and the eastern plains (Orinoquia) are drier with 500-1000 mm per year, favoring savannas and grasslands. Mean annual temperature is modulated by altitude, decreasing as elevation increases. The Caribbean lowlands maintain averages of 28-30°C year-round, while the Andes exhibit temperate climates (15-20°C), and the highest peaks experience freezing conditions (IGAC, 2012). For the methodological development of the maps, precipitation was obtained in raster format from databases of averages for the period 1976-2015 (IDEAM, 2025), temperatures by an international database (Fick and Hijmans, 2017) and elevation using de models of USGS-EROS (2018).

Soil properties are also heterogeneous. Soil pH varies nationwide, with neutral to slightly alkaline soils in central and eastern regions. Organic carbon content is higher in the Amazon and Andean regions, where Andisols with dark, organic-rich soils predominate, and lower in drier northern coasts and eastern plains Well-drained soils dominate highlands and steep slopes, while poorly drained soils are common in flatlands. Clay-rich soil is prevalent in Andean and Caribbean regions, whereas sandy or low-clay soils dominate the northern coast and eastern plains. Silt-rich soils occur mainly in river valleys and floodplains, particularly along major rivers such as Magdalena and Cauca. Lastly, slope gradients vary greatly across Colombia due to the three mountain ranges (Western, Central, and Eastern Cordilleras), contributing to its complex topography (IGAC, 2012). For the case of soil variables in the preparation of the maps, the Harmonized World Soil Data Base of FAO (2018) was used.

The vulnerability of the lands to Moko infection. The vulnerability of the lands to Moko infection was evaluated using a proposed index that assesses the effect of climate, soil, and spatial distribution of Musaceae production units in continental Colombia according to the equations described by Rodríguez *et al*. (2023a) in previous studies of the *Foc* R4T pathosystem, with base on expert criteria (Hughes, 1996; Procter *et al*., 2017; Sonneveld *et al*., 2023). To this end, through the capabilities of the QGis geographic information system (V3.38), the basic geographic information available in various digital formats was used.

The basic form of the Moko vulnerability index is shown in equation 1. The proposed expression is based on the idea that vulnerability to moko infection depends simultaneously on the interaction between climate and soil, as well as on the farm density in the area. Thus, even if soil and climate conditions potentially favor the incidence of moko, a low density of farms would result in relatively lower vulnerability.

$$VUP_{Moko} = V_{climate-soil} * FD \quad (1)$$

Where:

VUP_{Moko}: index of vulnerability of production units to Moko (considers the vulnerability of the land and the location of the production units of Musaceae).

$V_{climate-soil}$: land vulnerability index considers climatic elements and soil characteristics and obtained through equation 2, and

FD: (adjustment factor according to the density of production units of Musaceae).

The calculation of $V_{climate-soil}$ is represented as a differentiated weighting of the effects of climate and soil (Rodríguez *et al.*, 2023a). $V_{climate-soil}$ calculation assumes that if the effect of the climate ($E_{climate}$) is very low or not considerable ($E_{climate}$<0.5), the effect of the soil (E_{suelo}) is not considered. This is based on the principle that soil characteristics would not be relevant if climatic conditions do not allow the pathogen to develop

If $E_{climate}<0.5$; $V_{climate-soil} = E_{climate}$ (2)

If $E_{climate} \geq 0.5$; $V_{climate-soil} = 0.6 * E_{climate} + 0.4 * E_{soil}$ (3)

Assessment of the effect of the climate ($E_{climate}$). The indicator of the effect of climatic elements ($E_{climate}$) was expressed as a weighting of the mean annual precipitation and temperature (P and T, respectively) according to the importance of each of them (Equation 4). The result of the weighting between precipitation and temperature effects varies according to altitude. Beyond a threshold altitude, the influence of climate becomes progressively attenuated due to the environmental limitations that restrict the development of low-elevation musaceae plantations (Rodríguez *et al*., 2023a).

$$E_{climate} = \left(\frac{V_P * I_P + V_T * I_T}{\sum_{i=1}^{2} Ic_i}\right) * FH \quad (4)$$

Where, V_P assessment corresponding to the mean annual rainfall, V_T: assessment corresponding to the mean annual temperature, Ic: importance of each climatic element i, and FH: Altitude adjustment factor.

To obtain the precipitation and mean annual temperature values, the 30-second resolution raster maps available in *WorldClim* were used

(Fick and Hijmans, 2017). According to expert criteria, the values of precipitation and temperature were assessed on a qualitative scale of vulnerability in four classes: low, medium, high and very high, which, for algebraic purposes, correspond to values from 1 to 4. To obtain a continuous assessment, linear functions were used to associate precipitation and temperature values with continuous rating values within each class. In the Table 1, the ranges of precipitation and temperature values corresponding to each class and the importance in the weighting are shown.

The altitude adjustment factor (*FH)* was obtained as a function of altitude (*h*). Above 2000 m, this function gradually reduces the value of the altitude adjustment factor (*FH)*, and consequently the result of the $E_{climate}$ *index*, If *h*<2000 m, *FH*=1, so the index value is not affected $E_{Climate-Soil}$, and If h≥2000 m, then it is obtained through equation 5, based on the criteria used by Rodríguez *et al*. (2023a).

$$FH = 54.55 * e^{-0.002*h} \quad (5)$$

This expression was obtained by fitting an exponential function between the altitude threshold (2000 m), where FH equals 1, and an extreme altitude (5000 m), where FH approaches zero.

Table 1. Assessment of climate elements in relation to vulnerability scale to *Ralstonia solanacearum* in Musaceae crops.

Element	Class and rating (*Vi*)				Importance (*Ici*)
	Low (1)	Middle (2)	High (3)	Very High (4)	
Mean rainfall (mm/year)	<200	200 – 600	600 – 2000	>2000	10
Annual temperature (°C)	<12	12 – 18	18,1 - 25	>25	2

The altitude value of each pixel (*h*) was obtained from a digital elevation model of 1 arc-second (approximately 30 m) resolution (USGS-EROS, 2018).

Soil Effect Assessment (E_{Soil}). To assess soil characteristics, given the preliminary and exploratory nature of the study, the map from the FAO Harmonized World Soil Database (FAO-HWSD) was used (FAO, 2018). The selected characteristics corresponded to those relevant to Moko, and that, at the same time, were included in the database. The indicator of the effect of soil characteristics (E_{soil}) was expressed as a weighting of attributes associated with three soil qualities considered relevant as a predisposition factor to the pathogen (moisture retention, fertility, and waterlogging) (Table 2)

The valuations (*Vi*) corresponding to each soil attribute were weighted according to the relative importance assigned to each one (*Ii*), where the subscript *i* refers to each soil attribute considered (equation 6).

$$E_{soil} = \frac{V_A * I_A + V_L * I_L + V_{pH} * I_{pH} + V_{OC} * I_{OC} + V_{Drn} * I_{Drn} + + V_{Pen} * I_{Pen}}{\sum_{i=1}^{6} Is_i} \quad (6)$$

Table 2. Soil attributes used to determine vulnerability scale to *Ralstonia solanacearum* in Musaceae crops.

Soil property	**Indicator**
Moisture retention	Clay content (%)
	Silt content (%)
Fertility	Organic carbon content (%)
	Reaction (pH)
Waterlogging risk	Drainage class
	Slope

Where, V_A*:* assessment corresponding to the clay content in the soil, V_L*:* assessment corresponding to the silt content in the soil, V_{pH}: assessment corresponding to the reaction of the soil (pH), V_{OC}*:* assessment corresponding to the organic carbon content, V_{Drn}: assessment corresponding to the soil drainage class, V_{Pen}: assessment corresponding to the slope of the soil and Is_i: importance of each soil characteristic (subscript i refers to each soil characteristic).

The values of each soil attribute were classified on a qualitative vulnerability scale of four classes: low, medium, high, and very high, which, for algebraic purposes, correspond to values from 1 to 4 respectively (Table 3). To obtain a continuous assessment according to the values of clay, silt and organic carbon contents, reaction and slope of the soil, linear functions were used that associate soil attribute with continuous values of rating within each class.

Table 3. Assessment of soil characteristics in relation to vulnerability scale to *Ralstonia solanacearum* in Musaceae crops.

Element	Class and rating (*Vi*)				
	Low (1)	Middle (2)	High (3)	Very High (4)	Importance* (*Isi*)
pH	< 4.0	4.0 –5.0	5.0 – 6.0	>6.0	15
OC (%)	> 3.68	3.68 – 1.84	1.84 – 0.92	< 0.92	15
Drainage (Class)	6 and 7	5	3 and 4	1 and 2	10
Clay (%)	<15	15 – 30	30 – 50	>50	5
Silt (%)	<20	20 – 35	35 – 50	>50	6
Slope (%)	>25	12 - 25	3 – 12	<3	10

Note: Drainage classes: 1: Very poorly drained; 2: Poorly drained; 3: Imperfectly drained; 4: Moderately well-drained; 5: Well-drained; 6: Somewhat excessively drained; 7: Excessively drained. *Expert weight

Estimation of the density adjustment factor of production units (*FD*). The adjustment factor according to the density of Musaceae production units (*FD)* was obtained from a density index (*iD*) calculated from the location of 1441 production units of Musaceae crops in Colombia. Using the QGIS information system, a raster map of kernel density was generated considering a radius of 3° around each point. The resulting density index (*iD*) is continuously distributed, showing higher values in areas with greater point concentration and lower values in areas with fewer points.

Then, to obtain *FD*, a potential function was established to obtain values between zero and one according to an *iD* threshold (in this case 80). This value (iD = 80) was adopted as the upper limit for the fitting function, given its distinctly peripheral position within the overall point distribution. The use of this function allows the reduction rate to be lower and tend to one when the density index (*iD*) approaches the threshold of 80, and the reduction rate to increase when the density of production units approaches zero; If: $iD > 80$, $FD = 1$, which does not affect the $E_{climate\text{-}soil}$ *index*; and if $iD \leq 80$, then it is obtained through equation 7.

$$FD = 0.2554 * iD^{0.314} \quad (7)$$

This expression, through a power function, normalizes the *iD* values onto a scale of FD values that tends toward zero when *iD* is close to zero, and toward one when iD reaches 80.

Classifier Performance and Accuracy Assessment. For this step, selecting a representative sample of geographic locations for Musaceae production in Colombia was essential for analyzing land vulnerability to *R. solanacearum* race 2. The process began with the identification of the spatial distribution of banana and plantain cultivation areas across Colombia, including area affected by the disease. Based on this, a sampling frame was established to cover all potential zones of Musaceae presence. A suitable sample size was determined to ensure statistical representativeness without compromising manageability, resulting in a total of 1910 observations. A stratified sampling strategy was adopted to capture the variability in soil characteristics, climatic conditions, and elevation across the country. Within each stratum, a random sampling method was applied to select the specific geographic points used in the analysis.

The data matrix was composed of a set of observation vectors that represents each of the variables across *1910* geographic points and were labeled into five vulnerability categories (1 = very low to 5 = very high). Each vector contained the values of the variable for all observations. Thus, the matrix encompassed *1910* observations and *10* predictor variables relevant to the vulnerability of Musaceae-producing areas to *R. solanacearum* in Colombia. These variables included: altitude (ALT), annual mean precipitation (P), annual mean temperature (T), soil pH, organic carbon content (OC), drainage class (DC), percentage of clay and silt, land slope, and the farm density index (ID). This multidimensional dataset was used to characterize the edaphoclimatic and productive conditions potentially conducive to the occurrence and spread of Moko disease.

RESULTS AND DISCUSSION

Effect of Climate ($E_{Climate}$). The effect of climate integrated by precipitation and temperature variables, is decisive for the predisposition of *R. solanacearum* in Colombia. In the case of precipitation, approximately most of the territory has high or very high vulnerability to Moko, except for the northern part of La Guajira, where its tropical dry forest climate and arid and semi-arid humidity characteristics make it less vulnerability to the incidence of the disease and less prone to its spread (Figure 1a). Meanwhile, the mean temperature covers a little less than the precipitation of the territory with high or very high vulnerability to Moko (Figure 1b), with the remainder consisting of mountain ranges and elevated terrain that provide temperatures at which the pathogen's development may be affected and its infectivity possibly reduced, added to the fact that above 2500 masl there are no Musaceae plantations because low temperatures are a limiting factor for crop development (Figure 1c), with mean temperatures in these areas below the base temperature for Musaceae, which is 12°C (Rodríguez *et al*., 2018).

When observing the effect of climate, integrating the variables of precipitation, temperature, and altitude adjustment function, the result is that 90.83 % has high or very high vulnerability based on the country's climatic characteristics (Figure 1d). The Amazon, Orinoquia, and Pacific regions are represented by areas of very high vulnerability due to climate, as are some areas in the Andean and Caribbean regions.

Climate plays a fundamental role in the expression of health problems in banana and plantain crops (Fernández *et al*., 2022). On the one hand, climatic events such as heavy rainfall and tropical storms have contributed to the possible spread of pathogens, where climate variability and change are palpable realities that affect and will continue to affect the production of Musaceae in Latin America and the Caribbean in the coming years (Noleppa *et al*., 2021). The movement of pathogens can occur over short distances when vectors, wind, and rain are involved, while the spread of health problems over long distances occurs through the movement of plant material contaminated with pathogens (Nakato *et al*., 2018).

Precipitation, temperature, and altitude are variables that condition the incidence, severity, and spread of health problems in different pathosystems in Musaceae and must be considered when developing epidemiological scenarios and management strategies (Ocimati *et al*., 2022). Evidence in Costa Rica indicates that musaceae-producing areas subject to flooding are more prone to high levels of Moko Disease (Guzmán *et al*., 2025). In terms of temperature, regions with warmer thermal zones exhibit the greatest vulnerability. This corresponds to the Caribbean, Pacific, Amazonas and Orinoquia regions. Meanwhile, the vulnerability categories in the Andean region tend to show greater diversification due to the varying altitudes resulting from the eastern, central, and western mountain ranges that comprise this region.

However, water stress conditions caused by deficits lead to physiological weakness in the plant and make it more vulnerable to pathogen attack (Kubiriba *et al*., 2023). For their part, Bautista *et al*. (2016), in a study conducted in Quindío, Colombia, on banana cultivation, found that in the case of Moko, the higher the altitude, the lower the probability of the disease occurring, with the highest number of cases in this producing region found in the range of 1000 to 1500 masl.

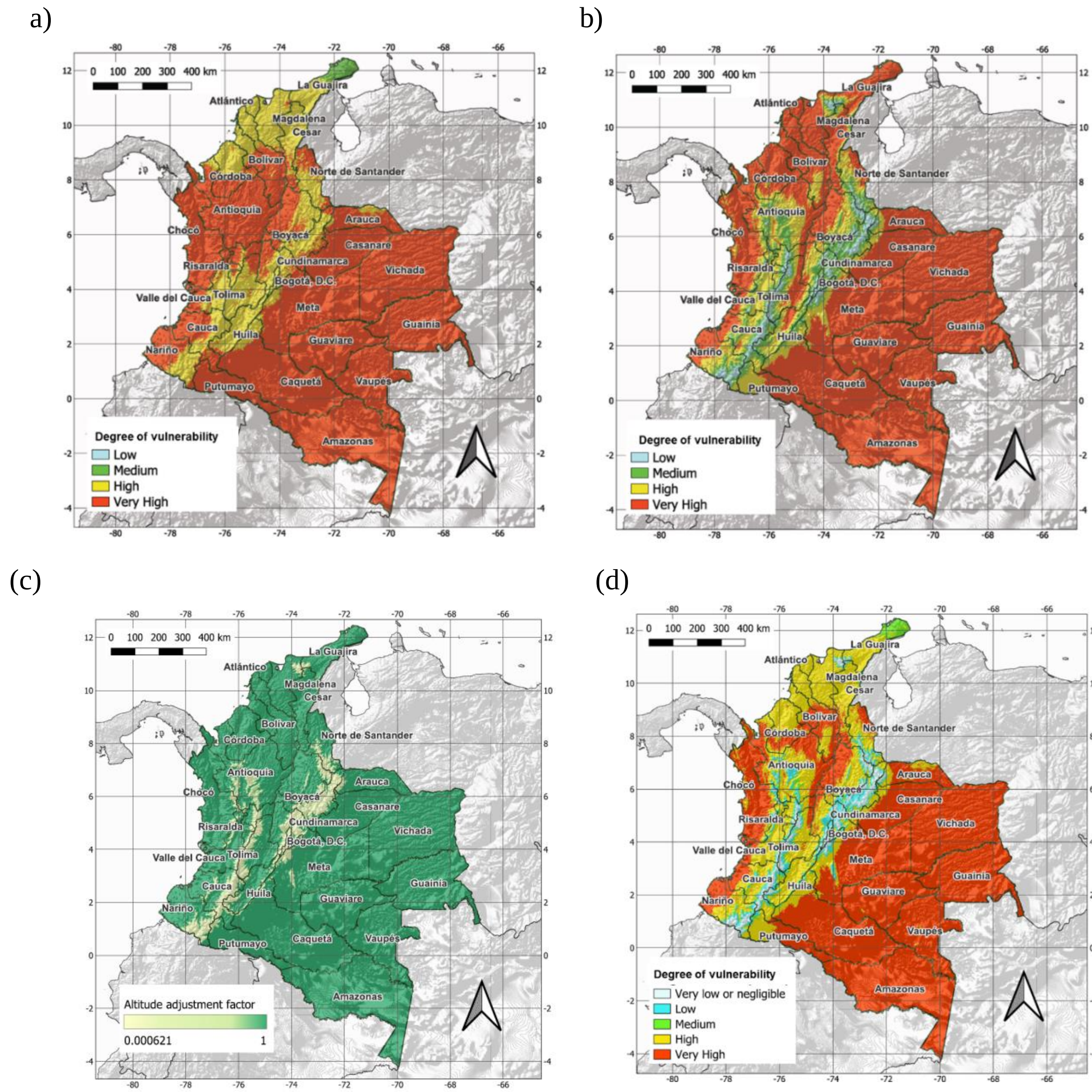

Figure 1. Distribution of climatic factors in Colombia and their relationship with Moko vulnerability. (a) Map of the effect of precipitation on the vulnerability of land to Moko Disease in Colombia; (b) mean temperature (°C); (c) altitude adjustment factor (masl); (d) effect of climate on the vulnerability of land.

High precipitation and soil moisture content have been reported as relevant factors in the spread, incidence, and severity of bacterial diseases in *Musa*, such as *Xanthomonas campestris* pv. *musacearum* in banana fields (Nakato *et al*., 2018). Studies that discriminate in detail the weight of different climatic variables indicate that around 60 % of the contribution to the dispersion and incidence of bacterial diseases is explained by mean temperature and annual precipitation. Specific conditions of high precipitation favor greater surface runoff and, with it, a greater possibility of dispersion of pathogens that inhabit the soil. Additionally, it is noted that dry climates are less likely to be severely affected by *Xanthomonas* wilt compared to areas with higher rainfall, which are conducive to the pathogen in Uganda (Kubiriba *et al*., 2023). Based on the findings for Colombia, in the regions identified as vulnerable, specifically the Pacific, Orinoco, Amazonas and Andean regions, rainfall exceeds 3000 mm per year. This factor directly influences the potential dispersal of the pathogen through surface runoff, creating conditions more conducive to increased inoculum pressure and possible increase in disease incidence. Other regions of the country categorized as having lower climate-related vulnerabilities correspond to precipitation levels below 3000 mm. This is most evident in the Caribbean region of Colombia, where Tropical Dry Forest conditions prevail compared to the rest of the country, where humid or very humid climates predominate.

Analyses that consider the climatic requirements for the establishment of pathogens and their effects in terms of variables that may favor a greater predisposition for the expression of diseases affecting the production of Musaceae are extremely important for determining epidemiology, as well as the implicit management factors for mitigating the possible effects of pathogens on these crops and the actions for control and health surveillance (Mbabazi *et al*., 2021; Rodríguez *et al*., 2023b).

Effect of Soil (E_{soil}). In the case of soil variables, the physical and chemical properties considered are presented in Figure 2a-f. In this regard, it can be observed that each variable is very heterogeneous in terms of its predisposition to pathogen development and its infectivity. However, when all these variables are integrated, a map of land vulnerability due to the soil factor is obtained (Figure 3a), in which it is possible to begin to differentiate regions of the country with different scales based on the overlap of edaphic variables that may or may not be predisposed to the pathogen.

The land vulnerability map based on the soil factor indicates that areas of the country with very high vulnerability to Moko represent 72,61%, high vulnerability represent 22,73 %, for a total of 96,38 % of areas with high or very high vulnerability to Moko disease.

For their part, the departments of Casanare and Arauca, which belong to the Orinoquia region, are highly vulnerable due to soil factors like pH, organic carbon, drainage, clay and slope. Considering, Arauca being one of the department main plantain-producing in Colombia.

The results found in the edaphic aspects show that soils with acidic pH correspond to areas of greater vulnerability. This is evident in the Caribbean, Pacific, Amazonas and Orinoquia regions, characterized by soil acidity and exhibiting high proportions of areas with high and very high vulnerability to this factor. Low organic matter content, on the other hand, shows a relation with areas of greater vulnerability to disease. In this regard, the Andean region presents lower levels of vulnerability for this variable compared to the Caribbean, Pacific, Amazonas and Orinoquia regions, where average organic matter values are around 2 %. Meanwhile, the Andean region, characterized by Andisol soils, has higher organic matter content (IGAC, 2012), making it less vulnerable.

Some studies have identified physical and chemical properties of soil that are conducive to *R. solanacearum* in bananas and plantains. In this regard, Bautista *et al.* (2016) pointed out that soils infected with moko are associated with low values of hydraulic conductivity and potassium saturation, as well as nutritional imbalances in cation ratios such as Mg/K and Ca+Mg/K for plantain cultivation. These results obtained by the authors in the coffee-growing region, related to poor drainage characteristics, help explain the findings regarding areas of the country with greater vulnerability based on soil texture and surface drainage capacity, combined with the slopes of the land. These factors, therefore, create conditions that predispose Moko disease to have a greater impact on banana crops. This corresponds to the Pacific, Caribbean, Amazon and Orinoquia regions, which present combinations of edaphic factors resulting in areas of greater soil vulnerability.

By integrating climate and soil factors and their respective variables into a single map, the vulnerability of land to Moko in Colombia from a soil and climate perspective can be obtained (Figure 3b). In this case the areas with high a very high of territory represent 90.65 %. Next, by incorporating into this map the locations of banana and plantain production units in Colombia, as well as the foci of the pathogen's presence in the country during the years 2021 to 2023 obtained from the health surveillance carried out by ICA and different projects developed by AGROSAVIA (Figure 4), we obtain a map of the vulnerability of production units and the location of the areas that are currently affected by the disease in Colombia.

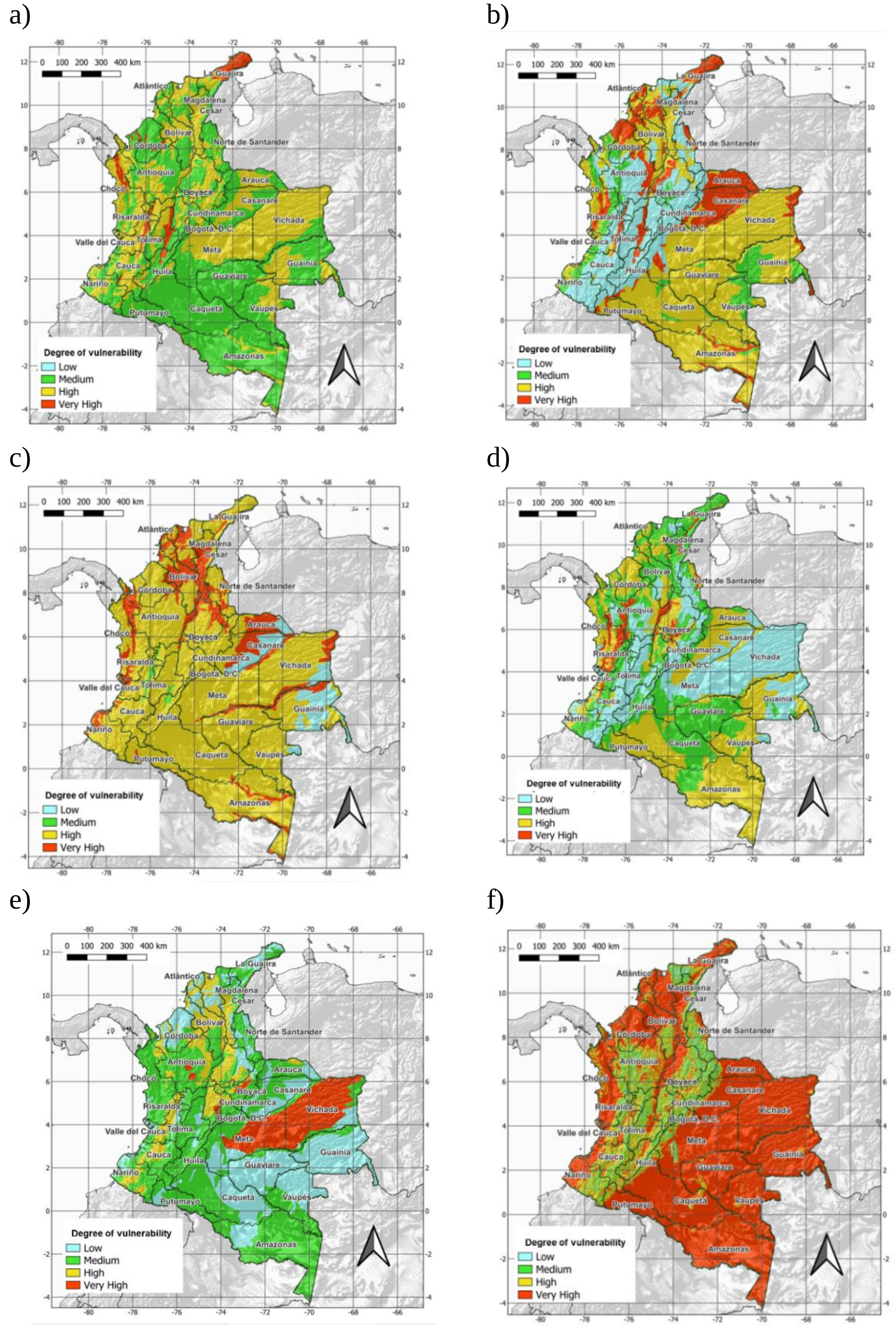

Figure 2. Variables associated with the soil factor (physical and chemical) and their degree of vulnerability to Moko Disease in Colombia. (a) Soil reaction; (b) Organic carbon; (c) Drainage; (d) Clay (%); (e) Silt (%) and (f) Slope.

When analyzing the proportion of areas with high and very high vulnerability at the territorial level departments with a greater predisposition to the pathogen are found (Figure 5). These departments should be given special attention to the design of specific management strategies, like biosecurity, plant eradication, agricultural practices and biological control, as well as to the prevention and avoidance of further spread within and outside these territories. The departments of Córdoba, Atlántico, Sucre, Bolívar, and Magdalena (Caribbean region); Meta, Casanare, and Arauca (Orinoquia region); Santander, Valle del Cauca, Huila, Putumayo, Norte de Santander, Antioquia and Cauca (Andean region); and Chocó (Pacific region) stand out as those regions with a high percentage of areas with high and very high vulnerability to the Moko effect of land and production units.

a) b)

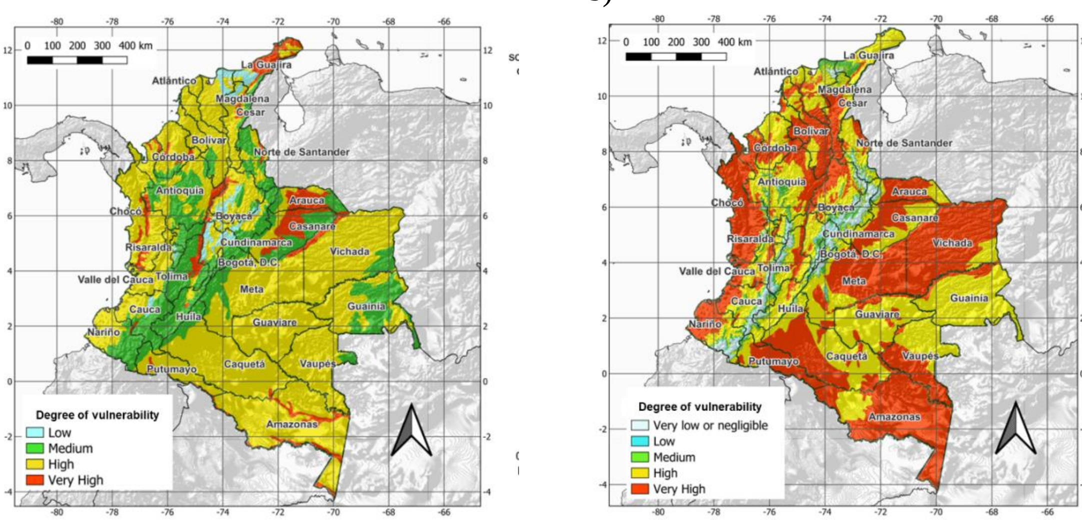

Figure 3. Integration maps of soil and climate variables related to Moko vulnerability in Colombia (a) Map of the effect of soil on the vulnerability of land; (b) Map of land vulnerability due to climate and soil factors.

Vulnerability of Production Farms to Moko Disease. With this definitive map (Figure 4), which integrates climate, soil, banana and plantain production units, and reports of disease outbreaks in recent years, it can be seen that 49.91 % of areas with high and very high vulnerability , which indicates that the areas with the presence of Musaceae (banana and plantain) hosts of the pathogen integrated with the climate and soil factors, offer a very different vulnerability panorama when not considering the density of Musaceae production units in the country.

By calculating the relative surface area of Moko and thus an index and degree of priority based on the vulnerability of land within the same department, a ranking was obtained which is presented in Table 4. Similarly, by calculating the representativeness of areas with high and very high s vulnerability at the departmental level, another priority ranking is presented based on areas very prone to a severe effect of the disease on current and potential Musaceae crops (Table 5).

One factor associated with the spread of Moko is the movement of surface water and the proximity of affected farms to water sources. In this regard, the persistence of the bacterium in crop water flows is high and is directly related to the spread of the disease in banana-producing areas in the department of Meta, Colombia (Tapiero *et al*., 2007). Similarly, in the coffee-growing region of the department of Quindío, Colombia, Bautista *et al*. (2016) found that a high proportion of farms with the presence of the pathogen were located near water sources such as rivers.

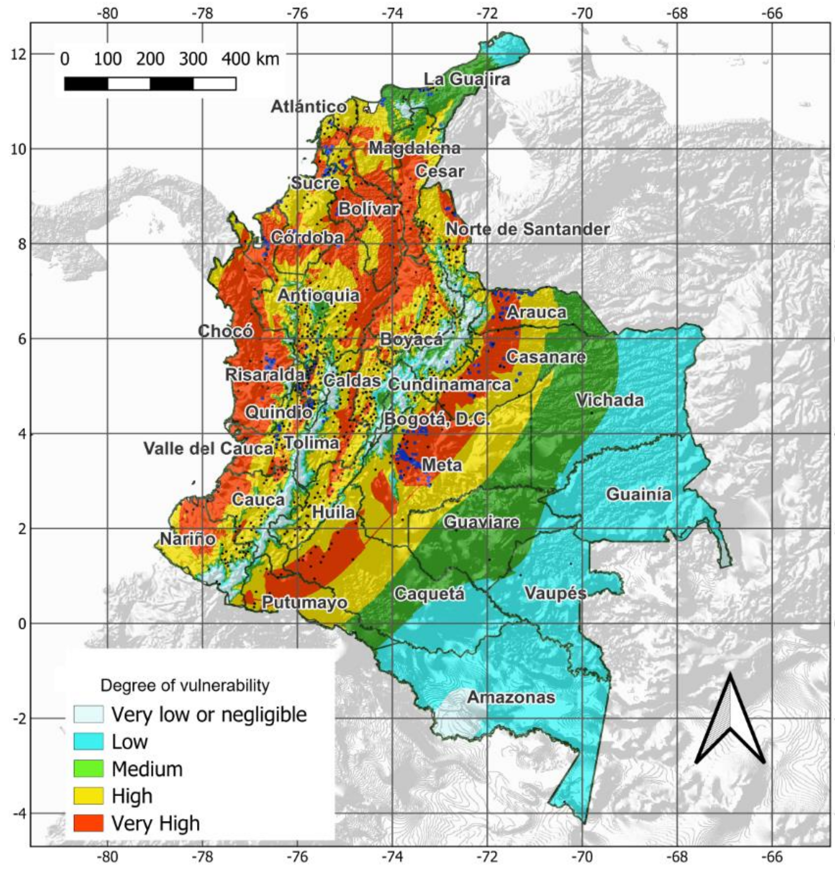

Figure 4. Map of the vulnerability of Musaceae production units to Moko disease in Colombia. Black dots: Musaceae production units; blue dots: Units affected by Moko.

Other non-soil and climate factors, such as alternative hosts (weeds), play a decisive role in the survival and spread of the pathogen (Kubiriba *et al*., 2023). There is evidence that mixing Musaceae cultivars, crop rotation, and associated crops reduce the incidence of the disease in these systems other than monoculture, as well as research pointing to biological control strategies, microbiome studies, and management practices to mitigate the effects of bacterial wilt in musaceae (Drenth and Kema, 2021; Ocimati *et al*., 2022).

Table 4 presents the relative weighted area and priority index of land vulnerability to Moko disease by department in Colombia, considering all vulnerability categories. Departments are then ordered from highest to lowest vulnerability based on the weighted calculation of the priority index and their respective categories. While it is true that, up to this point, consolidated interpretations can be obtained at the departmental or regional level from the maps, the results in Table 4 allow for the identification of vulnerability levels at the departmental level, considering all the identified categories. In this sense, departments belonging to the Pacific, Caribbean, and Orinoquia regions exhibit the highest levels of vulnerability, while in the Andean and Amazon regions, vulnerability decreases to medium to low categories.

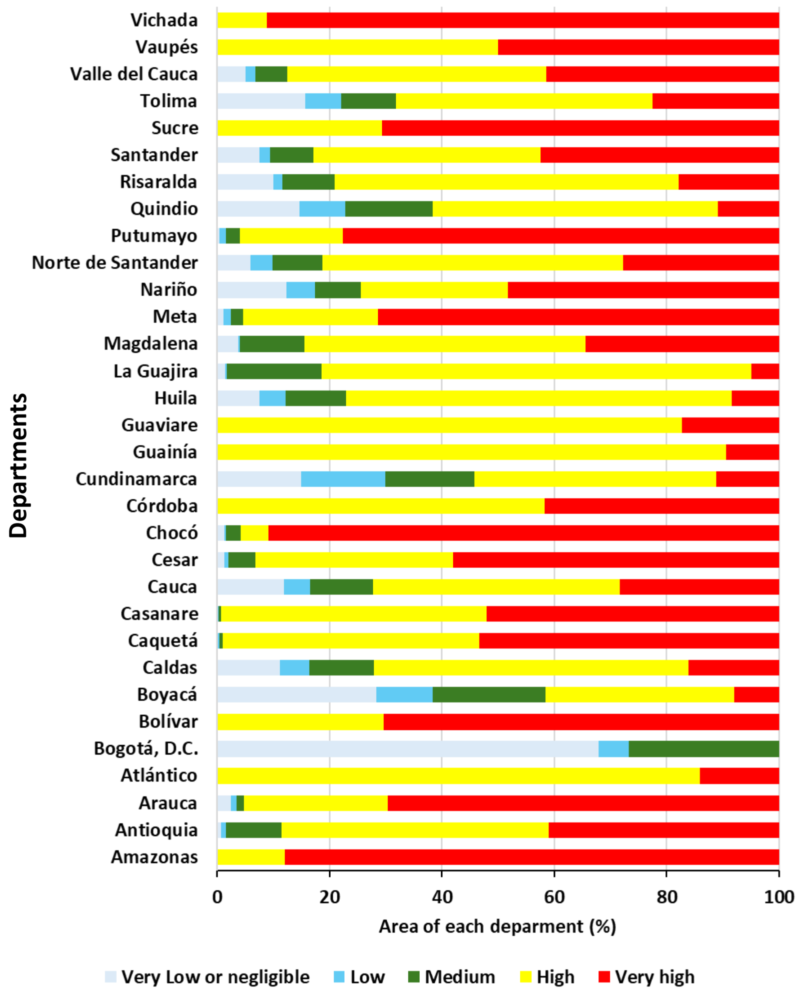

Figure 5. Proportion of areas of different levels of vulnerability of production units to the Moko disease in Colombia departments.

Table 5 shows a vulnerability ranking at the departmental level, considering only those areas with high and very high vulnerability for each department. These are then presented in order of greater relevance, and a priority index and its respective categorization at the departmental level.

Table 5 presents a ranking based on the vulnerability index, but in this case, only considering the proportion of areas with very high and high vulnerability categories per department, in relation to the total area of each, yields different results. From a practical standpoint, this represents departments where, if the pathogen were present in production areas, the impacts on banana production areas would be much greater. In this regard, the table 5 shows departments within the Orinoquia, Pacific, and Caribbean regions with high priority index values, corresponding to a very high interpretive classification. This priority index allows for the identification of areas representing zones of greater vulnerability, which must be addressed in sanitary surveillance programs and, additionally, be under integrated management schemes aimed at minimizing the negative effects of this disease on banana and plantain crops with greater emphasis than other areas with lower priority indices.

The results obtained provide a more robust approximation of the vulnerability of Musaceae production lands and units to Moko Disease in Colombia, which allows for the generation of scenarios for decision-making in terms of health surveillance, as well as disease prevention and management strategies that will be key to an integrated management approach to this health constraint of high importance for Colombia and other countries in Latin America and the Caribbean.

Table 4. Relative weighted surface area and priority index of land vulnerability to Moko disease by department in Colombia.

Department	Weighted vulnerability of production units	Priority Index	Priority Degree
Chocó	4.78	1.000	Very High
Sucre	4.71	0.984	Very High
Bolívar	4.70	0.983	Very High
Córdoba	4.42	0.924	Very High
Cesar	4.37	0.913	Very High
Antioquia	4.27	0.893	Very High
Casanare	4.20	0.878	Very High
Valle del Cauca	4.17	0.872	Very High
Atlántico	4.11	0.860	Very High
Meta	4.10	0.858	High
Santander	4.08	0.854	High
Putumayo	4.07	0.851	High
Magdalena	4.00	0.837	High
Norte de Santander	3.93	0.821	High
Arauca	3.84	0.803	High
Nariño	3.76	0.786	High
Risaralda	3.75	0.785	Medium
Cauca	3.72	0.778	Medium
Huila	3.66	0.765	Medium
Caldas	3.61	0.754	Medium
Tolima	3.53	0.738	Medium
Quindío	3.35	0.701	Medium
Caquetá	3.28	0.687	Medium
Cundinamarca	3.20	0.670	Medium
Guaviare	3.02	0.631	Low
Boyacá	2.83	0.592	Low
La Guajira	2.75	0.575	Low
Vichada	2.48	0.519	Low
Vaupés	2.04	0.428	Low
Guainía	1.99	0.416	Low
Amazonas	1.89	0.396	Low
Bogotá, D.C.	1.59	0.332	Low

Table 5. Index and ranking of high and very high vulnerability due to the potential effect of Moko disease at the departmental level in Colombia.

Department	High and very high vulnerability surface (km^2)	Priority Index	Priority Degree
Meta	72752.3	1.000	Very High
Antioquia	56305.7	0.774	Very High
Chocó	45821.5	0.630	Very High
Caquetá	40716.3	0.560	Very High
Casanare	36622.3	0.503	Very High
Bolívar	27154.5	0.373	Very High
Santander	25661.3	0.353	Very High
Córdoba	25455.6	0.350	Very High
Nariño	22772.2	0.313	High
Cauca	22526.9	0.310	High
Putumayo	20149.0	0.277	High
Cesar	19581.0	0.269	High
Valle del Cauca	17832.2	0.245	High
Norte de Santander	17800.4	0.245	High
Magdalena	17777.1	0.244	High
Tolima	16595.5	0.228	High
Arauca	15094.5	0.207	Medium
Huila	14071.3	0.193	Medium
Cundinamarca	12243.3	0.168	Medium
Sucre	10742.3	0.148	Medium
Boyacá	9722.5	0.134	Medium
Guaviare	5678.4	0.078	Medium
Caldas	5416.8	0.074	Medium
Atlántico	3383.1	0.047	Medium
Risaralda	2833.2	0.039	Low
Vichada	1717.8	0.024	Low
La Guajira	1271.1	0.017	Low
Quindio	1203.2	0.017	Low
Amazonas	0.0	0.000	Low
Bogotá, D.C.	0.0	0.000	Low
Guainía	0.0	0.000	Low
Vaupés	0.0	0.000	Low

CONCLUSIONS

Our results confirm that lands with acids soil, low organic matter, poor drainage in relation with edaphic factors; and high temperatures and rainfall considering climatic variables, present very high and high levels of vulnerability to

Moko under conditions of the main banana and plantain production areas of Colombia.

Vulnerability maps are presented integrating the evaluated edaphoclimatic variables that allow the identification of different ranges at the departmental level, as well as prioritization indices based on the proportion of high and very high vulnerability areas, which are very useful instruments for making health surveillance more effective, as well as the design of disease management strategies based on the combination of the soil and climate factors.

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