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Modelling of alluvial soil quality and production in permanent banana Harton plantations

Nelino Florida Rofner[1]*, *Cesar Augusto Gozme Sulca*[2], *Alex Rengifo Rojas*[3]

[1]*Department of Soil and Water Conservation Sciences, Faculty of Renewable Natural Resources, National Agrarian University of the Jungle, Tingo María, Huánuco, Peru*
[2]*Department of Environmental Sciences, Faculty of Renewable Natural Resources, National Agrarian University of the Jungle, Tingo María, Huánuco, Peru*
[3]*Department of Economic Sciences, Faculty of Economics and Administrative Sciences, National Agrarian University of the Jungle, Tingo María, Huánuco, Peru*

**Corresponding author: nelinof@hotmail.com*

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Abstract: Plantain is the most important crop for the Peruvian Amazonian population, developed in recent alluvial soils rich in nutrients, but fragile and susceptible to degradation. Therefore, the impact of permanent cultivation was evaluated, through modelling, on indicators of recent alluvial soil quality and production in plantations of *Musa paradisiaca* L. var. Harton, in the Aguaytia River valley, Peru. The treatments were areas with permanent plantain plantations of 2 (T0), 15 (T1), 4 (T2), and 5 (T3) years of management, evaluating soil physicochemical indicators and plantain production indicators. The results show significant differences for all yield and soil indicators evaluated, except for bulk density (Bd), clay fraction, soil organic matter (OM) and N. The modelling determined a significant positive impact on Bd and a significant negative impact on pH, P, pseudostem diameter and height, commercial fingers and bunch weight. In conclusion, the modelling shows trends of quality and yield reduction in 15 years of permanent management of plantain Var. Harton, and compromises the sustainability of the agroecosystem in the medium term.

Keywords: Entisols; modelling; *Musa paradisiaca*; permanent crop; recent alluvial soils

Peru cultivates around 225 000 ha of plantain with an average yield of 12 430 kg/ha and in the Ucayali region it represents the third largest crop with 27 580 ha and a yield of 13 890 kg/ha, equivalent to 1.54% of the national cultivated area as of 2018 (MIDAGRI 2021). In addition, 70% of the cultivation areas are located within the Amazon region, acquiring socioeconomic relevance, by contributing to feeding and income generation to the inhabitants of this region (INIA 2021) and of the main producers in Latin America and the Caribbean, Asia and Africa (FAO 2021).

Plantain usually grows well in soils of recent alluvial formation, which belong to the Entisols order, according to the soil taxonomy classification criteria, developed on materials recently deposited on valley bottoms and recent river terraces, and therefore, are soils with weak evidence of paedogenetic horizons (Buol et al. 1989). In addition, this order is characterised by presenting a high proportion of sand, clay contents less than 20%, slightly acid to neutral pH, and medium to high levels of exchangeable bases in the surface stratum (Chinchilla et al. 2011), conditions

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that favour cultivation. These fertility conditions occur due to the hydrological exchange between a river and its floodplain, which drive nutrient turnover seasonally and turn river floodplains into highly valuable ecosystems (Zurbrügg et al. 2012), with significant concentrations of nutrients, sediments and variable organic matter (Rudorff et al. 2014) and great potential for agricultural development, which so far has not received adequate attention despite their unique characteristics (Serrao et al. 2022).

Banana productivity varies depending on local conditions, the variety is grown, and management applied (Rajkishore et al. 2017), because of its direct relationship with the loss of soil quality and reduced crop productivity (Olivares et al. 2020a). Studies show that soil quality is directly related to productivity (Olivares et al. 2022b), especially alluvial soils rich in nutrients and organic matter (Rudorff et al. 2014), these aspects help reduce the rate of expression to diseases, improving nutrition and banana production (Segura et al. 2021).

Plantain presents great adaptability capacity (Rajkishore et al. 2017) and alluvial soils excellent conditions for this crop (Serrao et al. 2022). However, studies suggest evaluating the productive status (Martínez et al. 2022) through soil quality monitoring (Olivares et al. 2020a), taking into account that alluvial soils periodically present danger of flood erosion (Rajkishore et al. 2017), in addition, regardless of management Entisols soils present a high risk of degradation in tropical regions, due to their climate characteristics, low soil stability and nutrient loss by washing (Uribe et al. 2002; Olivares et al. 2022b), which can limit growth and productivity. In this context, through modelling, the work evaluated the impact of permanent cultivation of *Musa paradisiaca* L. Var. Harton, on recent alluvial soil quality and production indicators, in the Aguaytia River valley, Ucayali region, Peru.

MATERIAL AND METHODS

Study area. The research was carried out between November and December 2022 in Nuevo Progreso, district and province of Padre Abad, Ucayali-Peru region. The areas are located at coordinates: 445680E-9015185N (T1), 445622E-9015228N (T2), 445484E-9015392N (T3), and 445422E-9015512N (T0). It belongs to a very humid forest – Tropical Premontane, with an average temperature of 26.50 °C, relative humidity of 84%, and rainfall of 2 400 mm. The plantations are located in areas adjacent to the Aguaytía River (right bank), with soils of the Entisols order, sub-group typicudifluvets (Soil Survey Staf 2022); shallow soil, sandy to sandy loam texture, low penetration resistance (Rp), high bulk density (Bd) and neutral reaction, which receives at least two short floods (1–3 h) each year during the rainy season (November–April).

Management applied in the evaluated areas. We evaluated plantations of *Musa paradisiaca* L. var. Harton, known locally as "banana bellaco" and traditionally cultivated in the area as a permanent monoculture system, without fertilization plans and weed control with herbicide glyphosate® 36% (2 L/ha) at 60-day intervals. The plantation has a planting density of 3 × 3 m, manual harvesting with a 20-day interval and three plants per bush to avoid competition for nutrients and the appearance of pests and diseases.

Soil sampling and analysis. In each selected plantation, a sampling subarea (1 200 m^2) was delimited and 7 independent samples were extracted with the procedures of the Soil Survey Staff (2022). The analysis was performed at the Soil Water and Ecotoxicology Laboratory of the Universidad Nacional Agraria de la Selva, evaluating texture by the Bouyoucos hydrometer method, pH in distilled water (ratio 1 : 2.50) by the electrometric method, Ca^{2+}, Mg^{2+}, K^+, Na^+ and cation exchange capacity (CEC) extracted with ammonium acetate at pH 7 and determined by atomic absorption. Available P content by modified Olsen et al. (1954) and determined by colourimetry in UV-Vis spectra, and soil organic matter (OM) content by Walkley & Black (1934).

Statistical analysis. Differences between the evaluated areas were determined through analysis of variance and Tukey's post hoc tests ($P < 0.05$) for the comparison of means between indicators of soil quality and banana yield. IBM-SPSS 25 open-access software was used for processing. For modelling, multiple linear regression was used for experimental designs by estimating parameters by ordinary least squares (OLS) and generalized least squares (GLS), which are the main models that specify the behaviour of the indicators of banana crop yield and soil quality, widely used in this type of study (Olivares & Hernández 2020; Olivares et al. 2022c). Equation (1) shows the modelling as it corresponds to the indicator under analysis:

$$Y_i = \beta_0 + \beta_1 \times \text{Group} + \beta_2 \times \text{Aje}_j + \mu_i \quad (1)$$

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where:

$$\text{Group} = \begin{cases} |0, \text{control group} \\ |1, \text{group of the treatment} \end{cases}$$

$$\text{Age}_1 = \begin{cases} |0, 4, \text{and } 5 \text{ years} \\ |1, 15 \text{ years} \end{cases}$$

$$\text{Age}_2 = \begin{cases} |0, 5, \text{and } 15 \text{ years} \\ |1, 4 \text{ years} \end{cases}$$

$$\text{Age}_3 = \begin{cases} |0, 4, \text{and } 15 \text{ years} \\ |1, 5 \text{ years} \end{cases}$$

$\forall i = 1, 2, 3, \ldots, 48$ data;

Age_j – represented by Age_1, Age_2 and Age_3 independently expressed in Models 1, 2 and 3 through Equations (2), (3) and (4):

Model 1: $Y_i = \beta_0 + \beta_1 \times \text{Group} + \beta_2 \times \text{Age}_1 + \mu_i$ (2)

Model 2: $Y_i = \beta_0 + \beta_1 \times \text{Group} + \beta_2 \times \text{Age}_2 + \mu_i$ (3)

Model 3: $Y_i = \beta_0 + \beta_1 \times \text{Group} + \beta_2 \times \text{Age}_3 + \mu_i$ (4)

Y_i – the indicator of the yield or soil quality variable for data *i*;

β_0 – the effect of ages 4 and 5 in Model 1, 5 and 15 in Model 2 and 4 and 15 years in Model 3;

β_1 – the effect of the variable treatment group compared to the control group;

β_2 – the effect of age 15 relative to 4 and 5 in Model 1, age 4 relative to 5 and 15 in Model 2, and age 5 relative to 4 and 15 in Model 3;

μ_i – the information from other independent variables not observed in the model and is the stochastic component.

RESULTS AND DISCUSSION

Physicochemical and soil quality indicators. Table 1 shows the mean, standard deviation, and significance between the assessed areas. Significant differences were found for Rp, sand and silt; Bd and clay showed no differences. Significant differences were also found for pH, P, K^+, Ca^{2+}, CEC and Mg; OM and N showed no differences between the areas evaluated. There is a tendency of decrease in the indicators evaluated in 15 years of permanent management of banana in recent alluvial soil.

Physical indicators. Table 1 shows differences and means variability for Rp, sand and silt. The areas show sandy loam and loam soil for T0, with high % of sand, low in clay; in addition, there is a tendency to decrease the silt and clay fraction and increase sand in 15-year-old plantation (T1). Regarding the Rp shows tendencies of decrease, going from soft soil (Rp 1–2 g/cm^2) to very soft (Rp < 1 g/cm^2), this last one, explained by the decrease of the clay and silt fractions, and the increase of sand in 15 years of management; therefore, it does not represent the

Table 1. Soil physic-chemical indicators in plantations of *Musa paradisiaca* (n = 28)

Indicator	Treatment				Statistics	
	T1	T2	T3	T0	*F*	Sig.
Bd (g/cm^3)	1.41 ± 0.03	1.39 ± 0.05	1.43 ± 0.07	1.32 ± 0.03	1.54	0.23^{ns}
Rp (kg/cm^2)	0.64 ± 0.10	0.57 ± 0.06	0.58 ± 0.07	1.05 ± 0.13	42.70	0.00**
Sand (%)	62.57 ± 7.41	67.14 ± 4.38	62.57 ± 7.68	44.71 ± 10.55	11.29	0.00**
Clay (%)	14.29 ± 2.14	15.43 ± 2.23	13.43 ± 1.90	16.57 ± 4.28	1.67	0.20^{ns}
Silt (%)	23.14 ± 6.67	17.43 ± 4.65	24.00 ± 6.00	38.71 ± 11.34	10.00	0.00**
Class textural	Fr-ar	Fr- ar	Fr- ar	Franco	–	–
pH	7.10 ± 0.06	7.29 ± 0.06	7.40 ± 0.04	7.45 ± 0.03	63.33	0.00**
OM (%)	1.44 ± 0.22	1.48 ± 0.34	1.50 ± 0.13	1.57 ± 0.31	0.31	0.82^{ns}
N (%)	0.07 ± 0.01	0.08 ± 0.02	0.08 ± 0.01	0.08 ± 0.02	0.23	0.87^{ns}
P (mg/kg)	3.93 ± 0.27	5.94 ± 0.26	7.18 ± 0.14	5.92 ± 0.68	81.73	0.00**
K (cmol$^{(+)}$/kg)	47.39 ± 4.01	73.26 ± 2.78	58.79 ± 8.24	89.20 ± 5.81	73.23	0.00**
Ca (cmol$^{(+)}$/kg)	6.14 ± 0.15	6.08 ± 0.20	6.11 ± 0.35	6.67 ± 0.36	6.82	0.002**
Mg (cmol$^{(+)}$/kg)	0.87 ± 0.04	0.90 ± 0.13	0.98 ± 0.29	1.17 ± 0.24	3.10	0.04*
CEC (cmol$^{(+)}$/kg)	7.12 ± 0.14	7.13 ± 0.24	7.21 ± 0.61	7.99 ± 0.55	6.53	0.002**

Bd – bulk density; Rp – penetration resistance; OM – organic matter; CEC – cation exchange capacity; T0 – 2-year plantation; T1 – 15-year plantation; T2 – 4-year plantation; T3 – 5-year plantation; ± standard deviation; *F* – likelihood function; Sig. – significance; **highly significant; *significant; ^{ns}not significant

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danger of compaction. The soil shows a favourable physical condition for the crop, due to the weak root exploration capacity of the banana (CENTA 2018). The soils in the area belong to the Entisols order, subgroup typicudifluvets, are soils of recent alluvial formation developed on materials deposited by the Aguaytia River and have similar characteristics to those described by Chinchilla et al. (2011) and Rajkishore et al. (2017), describe these soils with a high proportion of sand and clay content of less than 20% in the surface stratum.

The trends of increasing sand and decreasing silt and clay fractions can affect water holding capacity, improved structure, porosity, and drainage (Soto 2008; CENTA 2018). This can be explained by the hydrological exchange between the river and its floodplain causing seasonal sediment renewal, generally incorporating silt and clay (Zurbrügg et al. 2012; Rudorff et al. 2014), however, under conditions of monoculture and herbicide application the soil remains bare and produces the opposite effect, soil erosion by the erosive action of floods in the area, losing clay and silt (Rodríguez 1990). In addition, the local climatic characteristics of high rainfall (> 2 400 mm) increases the risk of erosion and also explains the losses of these fractions and the reduction of Rp, due to the low stability of this type of soil (Uribe et al. 2002; Olivares et al. 2022b), which can limit growth and productivity, as can be seen in the results.

Chemical indicators. Chemical indicators are neutral to medium alkaline soils, low levels of OM and N, low to medium levels of P, medium levels of Ca and low levels of K^+, Mg^{2+}, and CEC, showing significant differences, except for OM and N. There are decreasing trends in the mean values of pH, P, K^+, Ca^{2+}, Mg^{2+} and CEC in 15 years of permanent cultivation, this decrease does not represent a risk in the pH level, but in the levels of the other indicators, although, considering the physical characteristics (high % of sand, low in clay and low Rp) of the area, there is a potential risk of decrease in the main bases and OM, typical behaviours registered in these types of soils (Olivares et al. 2022b; Serrao et al. 2022), also described in the main classification studies on Entisols soils of the Peruvian Amazon (ONERN 1972; Rodríguez 1990).

In general, river corridors have great potential for agriculture with particular characteristics (Serrao et al. 2022), slightly acidic to neutral pH, medium to high levels of exchangeable bases (Chinchilla et al. 2011; Rajkishore et al. 2017), rich in nutrients and variable organic matter (Rudorff et al. 2014; Serrao et al. 2022), therefore, banana is a species that adapts very well to this type of soil (Zurbrügg et al. 2012; Rajkishore et al.2017; Serrao et al. 2022), and plantations after 5 years of permanent cultivation under monoculture still maintain commercially acceptable soil conditions and production. However, in 15 years (T1) there is a tendency for the main macronutrients to decrease, generated by the high risk of flood erosion that these types of soils present (Rajkishore et al. 2017; Olivares et al. 2022a), compromising soil quality and crop production.

Yield indicators for plantain Harton. Table 2 shows the mean values, standard deviation and significant differences for all performance indicators assessed.

To shows higher values for all yield indicators and low values for the non-commercial fingers indicator, while T1 shows lower averages for all indicators evaluated. Therefore, the trend of decreasing production over time is demonstrated, which compromises the sustainability of the agroecosystem.

The local conditions are favourable for banana cultivation: altitude (< 2 200 m a.s.l.), rainfall (between

Table 2. Growth indicators in plantations of *Musa paradisiaca* (n = 28)

Indicator	Treatment				Statistics	
	T1	T2	T3	T0	F	Sig.
Pseudostem diameter (cm)	18.14 ± 2.61	20.86 ± 3.13	20.14 ± 1.07	22.86 ± 1.35	5.421	0.005**
Pseudostem length (m)	3.07 ± 0.22	3.38 ± 0.25	3.69 ± 0.25	4.16 ± 0.52	13.481	0.000**
Commercial fingers (united)	12.71 ± 4.82	17.57 ± 3.35	15.71 ± 3.73	22.71 ± 4.95	6.760	0.002**
Non-commercial fingers (united)	4.29 ± 0.95	3.86 ± 0.69	3.29 ± 0.49	3.29 ± 0.49	3.564	0.029*
Viable fingers (%)	73.55 ± 6.19	81.78 ± 3.37	82.25 ± 3.77	87.10 ± 1.84	13.198	0.000**
Cluster weight (kg)	4.84 ± 1.44	6.36 ± 0.99	5.66 ± 1.20	9.67 ± 1.82	16.083	0.000**

T0 – 2-year plantation; T1 – 15-year plantation; T2 – 4-year plantation; T3 – 5-year plantation; ± standard deviation; F – likelihood function; Sig. – significance; **highly significant; *significant

https://doi.org/10.17221/22/2023-SWR

Table 3. Bartlett's test of sphericity, correlation matrix and Kaiser-Meyer-Olkin (KMO) sampling adequacy measure for the indicators: banana crop yield and soil quality

Bartlett test of sphericity	Value	Description
Goodness-of-fit test		
Chi-square test (df = 136)	530.75	null hypothesis: yield and soil quality indicators are not correlated
P-value	0.0000***	
Correlation matrix		
Determinant	0.0000	linear correspondence exists
The measure of sampling adequacy		
KMO	0.672	good level

*, **, ****P* < 0.10, 0.05 and 0.01; df – degrees of freedom

2 000 and 3 000 mm), temperature (optimum average 25 °C), and alluvial plain soils with sandy texture and pH between 4.5 and 8 (CENTA 2018). In other words, fertile soils (Zurbrügg et al. 2012; Serrao et al. 2022) are capable of sustaining production at acceptable levels for up to 5 years of management (T3). For this management period (2, 4 and 5 years) the results are relatively similar and comparable with those of Hernández et al. (2007) in height and diameter of pseudostem (4.07 and 0.196 m, respectively), bunch weight (13.05 to 17.74 kg per bunch); also, Cayón et al. (2004) found height and diameter of 3.4 and 0.191 m respectively, with an average weight of 13.7 to 14.6 kg/bunch; Barrera et al. (2011) also found 17 to 20 fingers/bunch and an average weight between 5.36 to 8.10 kg/bunch, the latter very similar to the results found. Therefore, permanent banana cultivation is an option in recent alluvial soils for up to 5 years, after which mechanisms should be sought to maintain soil quality and production without causing agroecosystem degradation.

Correlation analysis and modelling

Linear correspondence analysis. Table 3 shoes the critical. value of the Chi-square distribution is 530.75 with degrees of freedom (df) of 136 functions used by Bartlett's test of sphericity proposes that it is sufficient evidence to reject the null hypothesis, for $P < 0.01$ of statistical significance. This test is reinforced by the result of 0.0000 in the determinant of the correlation matrix. Likewise, the exploratory principal component analysis is adequate for the sample because it manages to place at a good level with a value of 0.672 according to Kaiser-Meyer-Olkin (KMO).

Principal component analysis. The scale plot on the left side of Figure 1 suggests taking four components as having eigenvalues greater than unity and a value of 81.87% as the total cumulative variance.

The factors rotated by maximum variance are represented in the graphs in the last two columns on the right-hand side. Factor 1 is explained by altitude, commercial finger, cluster weight and commercial finger ratio. Factor 2, considers Bd, Sand, Ca and CEC as relevant. Factor 3 is explained by the indicator non-commercial finger and P, and Factor 4 considers OM and N as relevant, as they present factor loadings higher than 0.75 (for $n \leq 50$).

Modelling for soil physical indicators. The modelling of bulk density (Bd), arena and clay (Table 4) had their parameters estimated by OLS and GLS methods, making the stochastic component of each model homoscedastic and fit to the normal distribution function according to the values of the Chi-square distribution function of the White and Jarque-Bera test.

The variation of the independent variables manages to explain between 34.12% and 56.47% of the variation of Bd and sand according to Models 1, 2 and 3, this does not occur for the clay indicator, the R^2 is very low and the *F*-Fisher joint significance test does not show significance. Likewise, there is a positive effect of age 5 years on Bd in the case of Model 3, at the 10% level of statistical significance, while this does not reflect the same for the other models.

Modelling for soil chemical indicators. The modelling of pH (Table 5) shows positive influence through the intercept at 7.45 and negative influence through the group variable at 0.10, 0.19, and 0.25. Corresponding the age of 15 years explains negatively in 0.24 and the age of 5 years influences positively in 0.21 on the pH for the case of Models 1 and 3. The R^2 values show that the variation of the intercept, group, and age contribute in 80.07, 29.24 and 60.24% on the variation of the pH. These data are relevant because together they explain 1% for Models 1 and 3, as well as 5% of the pH for

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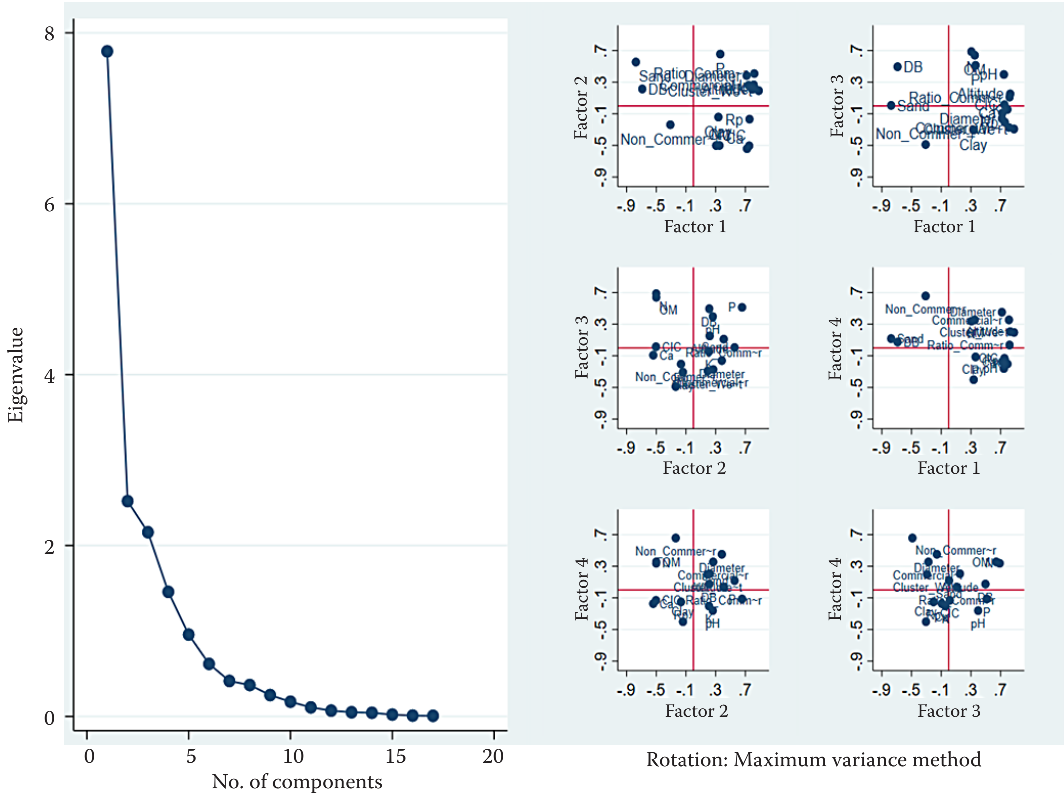

Figure 1. Scale plot of eigenvalues and factor loadings rotated by maximum variance method, the size of the data matrix (variables 15, samples 28, matrix = 420)

Model 2 according to the *F*-Fisher test. However, the variables group and age do not significantly explain the OM and N indicators.

Table 6 shows that the intercept, group and age have an influence ($P < 0.01$) on the indicators of P, Ca^{2+} and CEC. The relationship of the intercept

Table 4. Multiple linear regression models of soil quality indicators: bulk density (Bd), sand and clay using ordinary least squares (OLS) and generalized least squares (GLS) methods ($n = 28$)

Independent variable	Bb			Sand			Clay		
	Model 1[2]	Model 2[1]	Model 3[2]	Model 1[1]	Model 2[2]	Model 3[1]	Model 1[1,a]	Model 2[1,a]	Model 3[1,a]
Intercept	1.33***	1.33***	1.33***	44.71***	43.95***	44.71***	2.78***	2.78***	2.78***
Group (treatment = 1 and control = 0)	0.08***	0.09***	0.07***	20.14***	18.66***	20.14***	–0.13	–0.17**	–0.10
Age (years)									
15	–0.002	–	–	–2.29	–	–	–0.01	–	–
4	–	–0.03	–	–	4.59	–	–	0.11	–
5	–	–	0.04*	–	–	–2.29	–	–	–0.10
Coefficient of determination (R^2)	0.3412	0.4265	0.4024	0.5647	0.5478	0.5647	0.1066	0.1715	0.1613
Test									
F-Fisher ($df_1 = 2$, $df_2 = 25$)	6.02***	9.29***	9.17***	16.22***	17.73***	16.22***	0.2442	2.59*	2.40
White (Chi-square: df = 2)	–	1.82	–	3.58	–	3.84	1.24	1.59	1.53
Jarque-Bera (Chi-square: df = 2)	0.9933	0.6592	0.2492	0.5918	1.097	0.6939	3.0980	4.1580	3.862

[1]Parameters estimated by OLS; [2]parameters estimated by GLS; df_1 – degrees of freedom of the numerator; df_2 – degrees of freedom of the denominator; [a]dependent variable expressed in logarithmic terms; *, **, ***$P < 0.10$, 0.05 and 0.01

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Table 5. Multiple linear regression models of soil quality indicators: pH, soil organic matter (OM) and N using ordinary least squares (OLS) and generalized least squares (GLS) methods

Independent variable	pH			OM			N		
	Model 1[1]	Model 2[2]	Model 3[2]	Model 1[1]	Model 2[1]	Model 3[1]	Model 1[1,a]	Model 2[1,a]	Model 3[1,a]
Intercept	7.45***	7.45***	7.45***	1.57***	1.57***	1.57***	–2.57***	–2.57***	–2.57***
Group (treatment = 1 and control = 0)	–0.10***	–0.19***	–0.25***	–0.08	–0.10	–0.11	–0.02	–0.04	–0.04
Age (years)									
15	–0.24***	–	–	–0.05	–	–	–0.04	–	–
4	–	0.03	–	–	0.01	–	–	0.01	–
5	–	–	0.21***	–	–	0.04	–	–	0.03
Coefficient of determination (R^2)	0.8007	0.2924	0.6024	0.0365	0.0307	0.0338	0.0192	0.0107	0.0161
Test									
F-Fisher (df_1 = 2, df_2 = 25)	50.24***	4.57**	26.26***	0.47	0.40	0.44	0.25	0.14	0.21
White (Chi-square: df = 2)	5.34*	–	–	0.55	2.79	1.83	2.51	3.53	3.05
Jarque-Bera (Chi-square: df = 2)	1.012	0.576	0.2706	1.9860	1.971	3.0190	1.8370	1.8520	2.586

[1]Parameters estimated by OLS; [2]parameters estimated by GLS; df_1 – degrees of freedom of the numerator; df_2 – degrees of freedom of the denominator; [a]dependent variable expressed in logarithmic terms; *, **, ****P* < 0.10, 0.05 and 0.01

with the P, Ca^{2+} and CEC indicators is positive and the group variable is negative. There is an influence of the intercept on the indicators; likewise for the group variable on Ca^{2+} and CEC. However, the group variable has a significant influence ($P < 0.05$) on P for Models 1 and 2. The effect of 15 years is negative on P by 0.51 and 5 years is positive on P by 0.39.

Model for performance indicators. The variable group has a negative influence on diameter by 2.36 cm, height by 0.63 m and commercial finger by 6.07 units (Table 7), compared to the control group. Likewise, age 15 years explains negatively in 2.36 cm, 0.46 m and 3.93 units, while the intercept, manages to explain positively in 22.86 cm, 4.16 m and 22.71 units. As for Models 2 and 3 the variable group has the same occurrence because it manages to decrease in 3.71 and 3.37 cm the diameter, 0.78 and 0.93 m the altitude, and 8.50 and 5.57 units of the

Table 6. Multiple linear regression models of soil quality indicators: P, Ca and cation-exchange capacity (CEC) using ordinary least squares (OLS) and generalized least squares (GLS) methods

Independent variable	P			Ca^{2+}			CEC		
	Model 1[2,a]	Model 2[2,a]	Model 3[2,a]	Model 1[2,a]	Model 2[1]	Model 3[2,a]	Model 1[1]	Model 2[1]	Model 3[2]
Intercept	1.77***	1.77***	1.77***	1.90***	6.67***	1.90***	7.99***	7.99***	7.99***
Group (treatment = 1 and control = 0)	0.10**	–0.10	–0.20**	–0.09***	–0.54***	–0.09***	–0.82***	–0.82***	–0.88***
Age (years)									
15	–0.51***	–	–	0.01	–	–	–0.05	–	–
4	–	0.11	–	–	–0.04	–	–	–0.04	–
5	–	–	0.39***	–	–	0.001	–	–	–0.08
Coefficient of determination (R^2)	0.792	0.0446	0.4698	0.3663	0.4593	0.3586	0.4466	0.4461	0.3004
Test									
F-Fisher (df_1 = 2, df_2 = 25)	54.78***	0.57	10.67***	8.80***	10.62***	8.42***	10.09***	10.07***	11.35***
White (Chi-square: df = 2)	–	–	–	–	4.26	–	4.22	2.95	–
Jarque-Bera (Chi-square: df = 2)	2.636	1.397	1.21	0.8571	0.9557	1.0520	0.8811	0.9968	1.749

[1]Parameters estimated by OLS; [2]parameters estimated by GLS; df_1 – degrees of freedom of the numerator; df_2 – degrees of freedom of the denominator; [a]dependent variable expressed in logarithmic terms; *, **, ****P* < 0.10, 0.05 and 0.01

Table 7. Multiple linear regression models of banana crop yield indicators: diameter, altitude and commercial finger using ordinary least squares (OLS) and generalized least squares (GLS) methods (n = 28)

Independent variable	Diameter			Altitude			Commercial finger		
	Model 1[1]	Model 2[1]	Model 3[2]	Model 1[1]	Model 2[1]	Model 3[1]	Model 1[1]	Model 2[1]	Model 3[1]
Intercept	22.86***	22.86***	22.84***	4.16***	4.16***	4.16***	22.71***	22.71***	22.71***
Group (treatment = 1 and control = 0)	–2.36**	–3.71***	–3.37***	–0.63***	–0.78***	–0.93***	–6.07***	–8.50***	–7.57***
Age (years)									
15	–2.36**	–	–	–0.46***	–	–	–3.93*	–	–
4	–	1.71	–	–	–0.001	–	–	3.36	–
5	–	–	0.65	–	–	0.46***	–	–	0.57
Coefficient of determination (R^2)	0.3949	0.3328	0.2543	0.5815	0.444	0.5819	0.4431	0.4190	0.3558
Test									
F-Fisher (df_1 = 2, df_2 = 25)	8.16***	6.24***	4.94**	17.37***	9.98***	17.40***	9.94***	9.02***	6.90***
White (Chi-square: df = 2)	2.09	3.55	–	5.72*	3.24	5.17*	2.26	1.52	0.95
Jarque-Bera (Chi-square: df = 2)	0.0074	1.3600	0.5453	1.6570	0.8416	1.6950	1.6380	0.8630	0.6196

[1]Parameters estimated by OLS; [2]parameters estimated by GLS; df_1 – degrees of freedom of the numerator; df_2 – degrees of freedom of the denominator; [a]dependent variable expressed in logarithmic terms; *, **, ***P < 0.10, 0.05 and 0.01

commercial fingers; for the case of Model 3, the age of 5 years explains positively the height is 0.46 m.

The intercept, group and age variables do not explain the behaviour of diameter, height and commercial fingers. The F-Fisher values suggest rejecting the null hypothesis (P < 0.01), supported by the R^2 that manages to explain the variation of the indicator under analysis between 25.43 and 58.19%.

Table 8, the variable non-commercial finger, is positively explained by the intercept that picks up the age 4 and 5 years by 3.29 and the age 15 years by 0.71 for the case of Model 1. It also explains the age of 5 and 15 years by 3.29 corresponding to Model 2 and by the group by 0. 79 and inversely proportional for age 5 years by 0.79 concerning Model 3. Consequently, the variation of the intercept, group and age manages to explain 23.73%, 9.09% and 26.83% of the variation of non-commercial finger in Models 1, 2, and 3.

Cluster weight, the variable age 15 years explains negatively in Model 1, in terms of variation the in-

Table 8. Multiple linear regression models of banana crop yield indicators: non-commercial finger, bunch weight and commercial finger ratio using the ordinary least squares (OLS) method (n = 28)

Independent variable	Non-commercial finger			Bunch weight			Commercial finger ratio		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Intercept	3.29***	3.29***	3.29***	9.67***	9.67***	9.67***	0.87***	0.87***	0.87***
Group (treatment = 1 and control = 0)	0.29	0.50	0.79**	-3.66***	-4.42***	-4.07***	-0.05**	-0.09***	-0.09***
Age (years)									
15	0.71**	-	-	-1.16*	-	-	-0.08***	-	-
4	-	0.07	-	-	1.11	-	-	0.04	-
5	-	-	-0.79**	-	-	0.06	-	-	0.05*
Coefficient of determination (R^2)	0.2373	0.0909	0.2683	0.6557	0.6514	0.6109	0.6218	0.3745	0.4008
Test									
F-Fisher (df_1 = 2, df_2 = 25)	3.89**	1.25	4.58**	23.80***	23.35***	19.63***	20.55***	7.49***	8.36***
White (Chi-square: df = 2)	2.85	1.69	2.39	4.24	4.18	2.17	5.13	4.49	3.71
Jarque-Bera (Chi-square: df = 2)	2.487	5.293*	4.608*	1.255	1.074	0.9635	2.5450	5.356*	5.597*

df_1 – degrees of freedom of the numerator; df_2 – degrees of freedom of the denominator; *, **, ***P < 0.10, 0.05 and 0.01

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dependent variables contribute 65.57, 65.14 and 61.09% to the variation of the cluster weight. Regarding commercial finger is explained positively by the intercept in 0.87 and negatively by the variable group; additionally, the age of 15 years influences negatively Model 1 ($P < 0.01$) and age 5 years positively in 0.05 ($P < 0.10$) in Model 3. These models contribute in 62.18, 37.45, and 40.08% on the variation of the commercial fingers.

In general, the modeling of permanent management for 15 years generates:

(a) Positive impact on Bd ($P < 0.10$), the R^2 shows that age contributes 40.24% of the variation in Bd (Table 4). This behaviour would express a process of increase of the sand fraction, product of hydrological exchange between the river and its alluvial plain (Zurbrügg et al. 2012), which did occur and are negative trends for the crop.

(b) Negative impact on pH ($P < 0.01$), the R^2 shows that age contributes 80.07% of the pH variation (Table 5). This behaviour expresses an acidification process, although the pH remains at a neutral level, a typical condition for this type of soil (Uribe et al. 2002; Olivares et al. 2022a; Serrao et al. 2022), however, the reduction of pH is associated with the loss of Ca and Mg (Bohn et al. 1993; Rajkishore et al. 2017; Florida & Acuña 2020), which can be observed in the results (Table 2) and is possibly responsible for the reduction in crop yield.

(c) Negative impact ($P < 0.01$) on P levels, the R^2 evidence that age contributes 79.20% to P variation (Table 6). This behaviour may be linked to the extraction by the plant over time (Kalaivanan et al. 2018; Bolfarini et al. 2020) and applied management (Nunes et al. 2020) added to the decrease in pH and bases, observed in the results, which may alter the availability of this element (Ibrahim et al. 2022), behaviour that would be affecting the productivity and yield of the evaluated areas.

(d) Regarding the OM, N, Ca^{2+} and CEC indicators, there is no significant impact on these indicators, corroborated by the low R^2 values, which in terms of joint relevance are not significant. This does not mean that the mean values (Table 2) show a decreasing trend.

(e) Negative impact ($P < 0.01$) on the indicator's diameter, height, and commercial fingers (Table 7) and bunch weight (Table 8), the R^2 shows that the variable age contributes 39.49, 58.15, 44.31 and 65.57% of the variation of these indicators. The modelling shows the impacts of management in permanent banana plantations, with trends of degradation of soil quality and production, however, the observed negative changes occur in the medium and long term (5 to 15 years).

The study by Olivares et al. (2020a) establishes that commercial banana plantations in the regions of Aragua and Trujillo (Venezuela) were characterised by the intensive use of agrochemicals, registered in the last 20 years, generating a considerable reduction in productivity and the high incidence of fungal diseases due to the change and deterioration of the physical, chemical and biological properties of the soil in conjunction with environmental factors, being the content of Mg, the resistance to penetration, the total microbial respiration, the apparent density and the omnivorous free-living nematodes the most determining variables of the quality of the banana soil in areas with different levels of productivity. Likewise, in Venezuelan lacustrine and alluvial banana soils characterised by the change in land use from forest to plantation, the morphological properties of the soil such as biological activity, texture, dry consistency, reaction to HCl, and type of structure, allow distinguishing potentially suitable areas to obtain high levels of productivity and determine the main properties that are associated with the incidence of diseases such as banana wilt such as Zn, Fe, Ca^{2+}, K^+, Mn and Clay (Olivares et al. 2022c; Campos 2022).

The relationship between alluvial and lacustrine soil quality and banana production can be complex and influenced by several factors. For example, soil erosion can reduce soil quality, while the use of fertilizers can improve soil quality and banana production. Additionally, climate and weather conditions (Olivares 2018; Olivares et al. 2021) can also affect soil quality and banana production. The study by González-García et al. (2021b) and Garcia et al. (2021) shows that the bulk density, content of fine particles, organic matter, and carbon and microbial coefficient, were favourable for the high productivity lots.

The results mentioned above were compared with the findings of Rondón et al. (2021), which highlight those high yields from commercial banana farms are associated with high C content in stable aggregates, as well as in the more labile fractions of macro-organic matter. These results highlight the importance of the use of less recalcitrant organic fertilizers as a strategy for the sustainable management of banana cultivation and thus avoiding the incidence

https://doi.org/10.17221/22/2023-SWR

of banana wilt (Segura et al. 2022). Thus, according to Rey et al.(2020), and Olivares et al. (2021a), banana wilt in commercial plantations in Venezuela is associated with a fungal-bacterial complex and with some agroecological conditions characterised by silty soils presenting drainage problems and nutritional imbalances, typical of lacustrine soils that are accentuated by unappropriated fertilization regimens in the last years.

Our results presented here can be the scientific basis for environmental sustainability studies represented in conventionally managed banana areas in tropical countries such as Costa Rica, Colombia, Panama, and Venezuela, as established by the studies by Pittí Rodríguez et al. (2021), Montenegro et al. (2021), Olivares et al. (2022d) and Martínez et al. (2023) where they highlight the need to change the management of the agricultural environment for more sustainable practices linked to productive diversification and adequate fertilization within the soil enhancement strategy. Alluvial and lacustrine soils are formed by the deposition of sediments carried by rivers and lakes, respectively. These soils are rich in nutrients, particularly nitrogen and phosphorus, which are essential for plant growth (Olivares et al. 2020b, 2022b). However, these soils can also be prone to soil erosion and leaching of nutrients, which can affect soil quality and banana production. Therefore, understanding the dynamics of soil quality in alluvial and lacustrine soils is crucial for sustainable banana production.

CONCLUSION

Differences were found for all yield and soil indicators evaluated, except for bulk density, clay fraction, OM and N. In 15 years of permanent cultivation of *Musa paradisiaca* L. var. Harton, the soil shows an increase in % sand, Bd and a decrease in clay, silt, Rp, OM, N, P, Ca^{2+}, Mg^{2+}, K^{+}, and CEC. The modelling determined a significant positive impact on Bd and a significant negative impact on pH levels, P, pseudostem diameter and height, commercial fingers and bunch weight, but no significant impact on OM, N, Ca^{2+}, and CEC. Negative changes occur in the medium and long term (5 to 15 years), an aspect that can be corrected with management alternatives (use of cover crops, living barriers and organic fertilization) in permanent plantations of *M. paradisiaca* on alluvial soils in this region.

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