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Article

Efecto de tres sistemas de producción sobre el estado de la fertilidad física del suelo

Effect of three production systems on the physical fertility status of the soil

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Abstract

The physical fertility of the soil is important, and land use systems can modify it. The objectives of this study were to determine the influence of sampling depth (SD) and of the agricultural, forest and livestock land-use systems (LUS) on the physical properties of a tropical soil, and to establish whether the sampling type (ST) affects compliance with the assumptions of normality and homoscedasticity, as well as the statistical significance of the effects of systems and depth. A simple soil sampling (SS) and a composite soil sampling (CS) were performed at 0 to 10 cm and 10 to 20 cm deep. Texture, bulk density, field capacity, permanent wilting point, usable moisture, aggregate stability, total porosity and saturated hydraulic conductivity were determined. The LUS had significant effects on field capacity and on the permanent wilting point with CS, and on aggregate stability with SS and CS. The only variable that showed statistically significant differences for the various SD was aggregate stability, with both types of sampling; these impacted the normality and homoscedasticity of data for bulk density and total porosity. The CS exhibited non-compliance with normality, unlike the SS, it also influenced the significance of the effects of LUS and SD, as well as their interaction with each other. The pasture system exhibited the most convenient values for the physical variables from the agronomic point of view.

Key words: Agricultural, fertility, rubber, sampling, pasture, physical properties.

Resumen

La fertilidad física del suelo es importante y los sistemas de uso del suelo pueden modificarla. Los objetivos fueron determinar la influencia de la profundidad de muestreo (PM) y de los sistemas de uso del suelo (SUS) agrícola, forestal y pastizal sobre las propiedades físicas de un suelo tropical, y establecer si el tipo de muestreo (TM) incide en el cumplimiento de los supuestos de normalidad y homocedasticidad, así como en la significancia estadística de los efectos de los sistemas y las profundidades. Se realizó un muestreo de suelo simple (MS) y uno compuesto (MC) a las profundidades 0 a 10 cm y 10 a 20 cm. Se determinó la textura, densidad aparente, capacidad de campo, punto de marchitez permanente, humedad aprovechable, estabilidad de agregados, porosidad total y conductividad hidráulica saturada. Los SUS tuvieron efectos significativos sobre la capacidad de campo y punto de marchitez permanente con el MC, y estabilidad de agregados para los MS y MC. La única variable que presentó diferencias estadísticamente significativas para las PM fue la estabilidad de agregados en ambos tipos de muestreo; estos incidieron en la normalidad y homocedasticidad de datos para densidad aparente y la porosidad total. El MC mostró un no cumplimiento de la normalidad a diferencia del MS, también en la significancia de los efectos de los SUS y las PM, así como en su interacción. El pastizal presentó los valores más convenientes de las variables físicas desde el punto de vista agronómico.

Palabras clave: Agrícola, fertilidad, hule, muestreo, pastizal, propiedades físicas.

Introduction

Physical soil fertility is the ability of the soil to provide optimum physical conditions that support productivity, reproduction, and plant quality (Abbot and Murphy, 2007); it can be determined by studying the physical properties of the soil: texture, bulk density, water storage capacity, porosity, stability of aggregates and hydraulic conductivity (Osman, 2013; Weil and Brady, 2017).

Knowledge of the physical properties of a soil helps evaluate its condition, and it provides information on the change of use and the impact that agricultural, livestock and forestry practices have on its deterioration or functioning (Estrada-Herrera *et al.*, 2017); furthermore, agricultural intensification is considered to generate a reduction in physical fertility (Semarnat, 2015).

Research has been conducted worldwide to test the impact of land use change on soil fertility (Fernández *et al.*, 2016; Kassa *et al.*, 2017; Cantú *et al.*, 2018; Yáñez *et al.*, 2018). Some authors cite that physical properties such as bulk density and field capacity are better in forestry systems than in agricultural systems (Fernández *et al.*, 2016); others conclude that agricultural soils exhibit a state of low physical fertility due to the activity to which they are subjected (Cantú *et al*., 2018; Yáñez *et al*., 2018).

In some studies (Fernandez *et al*., 2016; Kassa *et al.,* 2017), analysis of variance (*ANOVA*) is used to detect differences due to land use, without mentioning whether the data obtained met the basic assumptions of normality and equality of variances (homoscedasticity). Homoscedasticity is one of the most important properties for some of the parametric inferential methods, since it is a condition that must be met in order to perform an *ANOVA*; it is present in data sets in which the variables have the same or very close variance, while the errors of a data set in comparison should fit the normal distribution (Sokal and Rohlf, 2009). If these basic assumptions are not met, other analysis alternatives, such as nonparametric tests (Sokal and Rohlf, 2009), are considered in order to obtain more reliable results.

The objective of this study was to characterize the physical properties, at two different depths, of a tropical soil with agricultural, forestry and pasture uses utilizing simple and composite sampling methods to determine: a) the impact of sampling methods on compliance with normality of data and homoscedasticity of variances; b) the impact of sampling methods on the determination of the statistical significance of land use system and depth effects; c) the effect of land uses and depths on physical variables; d) which land use system presents the most convenient values, from an agronomic point of view, for the physical variables.

Materials and Methods

Study area

The study area is located in *General Felipe Ángeles ejido*, *San Juan Mazatlán* municipality, state of *Oaxaca*, its geographic coordinates are 17°20'35.98'' N and 95°19'8.11'' W, and its altitude, 63 masl. The *ejido* is part of the Southern Gulf Coastal Plain physiographic province, in the *Veracruz* Coastal Plain sub-province, and its relief is characterized by consisting of low hills (INEGI, 2001a, 2001b, 2001c). The types of rocks present are sedimentary rocks such as sandstone, conglomerate of the Cenozoic era, and limestone of the Mesozoic era, as well as intrusive igneous rocks such as granite of the Paleozoic era (Inegi, 2019). The average annual precipitation is 2 020.3 mm yr^{-1}; the average temperature ranges between 20.3 and 30.8 °C, with an average of 25.6 °C (Krasilnikov *et al.*, 2013; Servicio Meteorológico Nacional y Comisión Nacional del Agua, 2019), and the climate is warm humid with abundant rainfall in summer (Inegi, 2019). The dominant soils are luvisols and fluvisols (Inegi, 2019).

Most of the *ejido*'s vegetation consists mainly of introduced grasses such as *Brachiaria brizantha* (A. Rich.) Stapf cv. *Insurgente*, used for cattle feed; plantations of Persian lemons (*Citrus latifolia* Tanaka) for export; of maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.) crops, for self-supply, and of commercial *Hevea brasiliensis* (Willd. ex A. Juss.) Müell. Arg. forests*,* for rubber production.

Soil sampling and laboratory analysis

In order to locate the land-use systems on umbrihumic Luvisol, a walk-through was conducted, and sampling was performed in July 2018 in the forest systems (FS): rubber plantation with 30 years of management (17°21'20" N, 95°20'21" W) with a planting distance of 6 m x 3 m (556 trees ha^{-1}) and management practices consisting mainly of pest and disease control; pasture or livestock (SP), with extensive cattle grazing with the *Insurgente* variety for 25 years (17°21'15" N, 95°20'22" W), allowing the soil to rest during the dry season (February to May); and agricultural (AS), with Persian lemon with 10 years of management (17°20'59" N, 95°18'53" W) and manual planting of intercropped corn or beans during the rainy season (May to November).

In each land use system, four randomly selected 20 x 20 m sampling areas were established, according to Kassa *et al.* (2017). In the FS and AS, the sampling areas were located between the rows of rubber and Persian lemon trees, respectively. Two sampling types (ST) were considered: at the center of each area a simple soil sampling (SS) was performed, with a straight cut shovel; likewise, 16 subsamples were collected in each area, using the composite sampling (CS) procedure of Carretero *et al.* (2016). The sampling was carried out at two depths: 0 to 10 cm (SD1) and 10 to 20 cm (SD2). 48 soil samples total were obtained —24 simple and 24 composite—, considering the four areas, the three systems and the two sampling depths (SD).

Soil samples were transported in plastic bags, air-dried without direct exposure to sunlight (Semarnat, 2002). Once the samples were dry, they were ground with a wooden mallet and sieved through a 2 mm mesh (Hernández *et al*., 2017).

The evaluated physical properties were: bulk density (*BD*), by the paraffinized lump method (Blake, 1965); texture, by the Bouyoucos method (Gee and Bauder, 1986); field capacity (*FC*), with the pressure cooker, and permanent wilting point (*PWP*), with the pressure membrane; the above determinations were made following the norm NOM-021-RECNAT-2002 (Semarnat, 2002). The aggregate stability (*AgS*) was assessed according to Yoder's method, using a 0.25 mm sieve (Amézketa, 1999), the saturated hydraulic conductivity (*Ksat*), utilizing a constant load permeameter on saturated samples (Klute and Dirksen, 1986), the usable humidity (*UH*), as the difference between *FC* and *PWP*, and the total porosity (*TP*), as a function of *BD* and actual density (Weil and Brady, 2017).

Statistical analysis

The statistical analysis was performed with a 3 x 2 factorial design, *i.e*., three land-use systems by two sampling depths, with four replications. The Shapiro-Wilk (S-W) normality test ($P<0.05$) and Levene's homoscedasticity of variances test (L_t) ($P<0.05$) were applied (Zar, 2014). Subsequently, a two-way analysis of variance (*ANOVA*) was performed with equal replications (Zar, 2014). The decision rule for the significance of the factors was as follows: $0.01<P<0.05$ (*, moderate);

$0.001<P<0.01$ (**, strong); y $P<0.001$ (***, very strong). Variables that did not meet the assumptions of normality of data or homoscedasticity of variances were analyzed using a nonparametric Aligned Rank Transformation (ART) test which "aligns" the data before applying averaged intervals, after which common *ANOVA* procedures can be used (Mangiafico, 2016).

Tukey's mean comparison tests ($\alpha = 0.05$) (Zar, 2014) were performed to determine significant differences by land use systems, sampling depths, and their interaction. When there was a significant difference in the interaction between systems and depths in the *ART-ANOVA*, the mean values corresponded to the average of the variable in the four sampling areas of each system, and comparisons were made with the pairwise comparison test. The RStudio software for R 3.6.1 (R Core Team, 2018) and the *Microsoft Excel*® software package (Microsoft, 2018) were used for the statistical analysis. The mean values of the physical variables of the land-use systems and sampling depths were compared using the "higher is better" criterion, in which those properties with a high value (*TP*, *FC*, *PWP*, *UH*, *AgS*, and *Ksat*) were grouped, and the "lower is better" criterion, for those properties (*BD*) for which a low value is more convenient (Hernández-González *et al.*, 2018).

Results and Discussion

Texture classes obtained with the Texture Triangle (Weil and Brady, 2017) and the mean values for the percentages of sand, silt and clay in the three land-use systems analyzed with simple sampling (SS) were sandy-clayey loam (SCL), sandy loam (AS) and loam (PS); for the composite sampling (CS), they were sandy-clayey loam, clayey loam, and sandy-clay loam, respectively. The textures determined on the basis of the mean sampling depth values (SD1 and SD2) using SS were loam and clay loam, respectively; for CS, they were sandy loam and sandy-clayey loam, respectively. According to the above, from the point of view of texture, the soils are homogeneous, given that in all cases the texture was loam. Consistently with the results of this study, Cruz-Ruiz *et al.* (2012) did not obtain differences in texture ascribable to the LUS between three land-use systems (LUS) in Mexico.

Normality and homoscedasticity

Table 1 shows that all variables met the assumption of normality, with the exception of the saturated hydraulic conductivity (*Ksat*), when simple sampling was used. With the composite sampling, *BD*, total porosity (*TP*) and *Ksat*, failed to meet this assumption. All variables with the sampling types met the homoscedasticity assumption, with the exception of *Ksat*. Santiago-Mejía *et al.* (2018) that *Ksat* is a physical property that exhibits high spatial variability. For variables that did not comply with normality or homoscedasticity, the effect of the factors on these variables was determined using the *ART-ANOVA* test (Mangiafico, 2016).

Table 1. Shapiro-Wilk normality test (S-W) and Levene's homoscedasticity (L_t) test for the physical variables evaluated.

Test	**TM**	***BD* Mg m^{-3}**	***TP* %**	***FC* %**	***PWP* %**	***UH* %**	***AgS* %**	***Ksat* cm h^{-1}**
S-W	MS	0.98^{ns}	0.96^{ns}	0.46^{ns}	0.52^{ns}	0.46^{ns}	0.96^{ns}	***
	MC	**	*	0.15^{ns}	0.96^{ns}	0.19^{ns}	0.72^{ns}	**
L_t	MS	0.95^{ns}	0.23^{ns}	0.98^{ns}	0.59^{ns}	0.58^{ns}	0.24^{ns}	*
	MC	0.52^{ns}	0.15^{ns}	0.90^{ns}	0.90^{ns}	0.41^{ns}	0.77^{ns}	*

Significance: * = Moderate ($P<0.05$); ** = Strong ($P<0.01$); *** = Very strong ($P<0.001$); ^{ns} = Not significant; ST = Sampling type; SS = Simple sampling; CS = Composite sampling; *BD* = Bulk density; *TP* = Total porosity; *FC* = Field capacity; *PWP* = Permanent wilting point; *UH* = Usable humidity; *AgS*= Aggregate stability; *Ksat* = Saturated hydraulic conductivity. A value above 0.05 denotes normality or homoscedasticity of the variable.

ART-ANOVA and *ANOVA*

Table 2 shows that, with *ART-ANOVA*, the *BD* variable with composite sampling exhibited a significant difference only for the interaction between land-use systems and sampling depth. Based on the above, *post-hoc* mean comparison tests were performed comparing the mean values obtained in the three levels of the systems factor and the two levels of the depth factor, in order to record possible significant differences between pairs of means. For *Ksat* with simple sampling, the results indicated that significant differences were found for the depth factor, as well as for the interaction between systems and depth.

Table 2. *ART-ANOVA* and *ANOVA* for the effect of land use systems, depths and their interaction.

VF	ST	***BD*** **Mg m^{-3}**	***TP*** **%**	***FC*** **%**	***PWP*** **%**	**UH %**	***AgS*** **%**	***KsAT*** **cm h^{-1}**
LUS	MS	*	*	0.20^{ns}	0.17^{ns}	0.61^{ns}	*	0.15^{ns}
	MC	0.13^{ns}	0.40^{ns}	**	***	0.57^{ns}	***	0.06^{ns}
SD	MS	0.45^{ns}	0.95^{ns}	0.33^{ns}	0.37^{ns}	0.51^{ns}	**	**
	MC	0.06^{ns}	0.18^{ns}	0.28^{ns}	0.65^{ns}	0.19^{ns}	**	0.92^{ns}
LUS*SD	MS	*	**	0.25^{ns}	0.90^{ns}	0.09^{ns}	0.87^{ns}	*
	MC	*	0.25^{ns}	0.20^{ns}	0.91^{ns}	*	0.84^{ns}	0.41^{ns}

* = Moderately significant differences ($P<0.05$); ** = Strongly significant differences ($P<0.01$); *** = Very strongly significant differences ($P<0.001$); ^{ns} = Not significant; LUS= Land-use system; SD = Sample depth; ST = Sampling type; SS = Simple sampling; CS = Composite sampling; *BD* = Bulk density; *TP* = Total porosity; *FC* = Field capacity; *PWP* = Permanent wilting point; *UH* = Usable humidity; *AgS* = Aggregate stability; *Ksat* = Saturated hydraulic conductivity.

In the case of the variables analyzed under *ANOVA*, significant differences were obtained only for the bulk density using simple sampling for the systems factor, as well as for the interaction of the systems with the depths. Also, there were significant differences in the case of total porosity with the simple sampling for the systems factor and for the interaction between systems and total porosity. Likewise, significant differences were recorded for field capacity with composite sampling for the systems factor; while, for the permanent wilting point the significant differences were obtained for the land use systems factor using the composite sampling. Finally, it should be noted that there was significance in the interaction between systems and depths for usable humidity with the composite sampling, as well as for aggregate stability for both the systems and depth factors using the two types of sampling.

Table 3 shows that the pairwise comparisons test exhibited significant differences in the mean values for bulk density (*BD*) at SD1 with the agricultural and pasture systems, of 1.49 and 1.37 Mg m^{-3}, respectively; while the mean *BD* values at the same depth with the forest system and the pasture system were 1.51 and 1.37 Mg m^{-3}, respectively. For *TP* with composite sampling, the ART-*ANOVA* test showed no significant differences between the studied factors.

Table 3. Mean comparison test of soil physical parameters for the LUS*SD interaction, using exponent letters to indicate the means with significant differences.

ST	**SD**	**LUS**	***BD* Mg m^{-3}**	***TP* %**	***FC* %**	***PWP* %**	***UH* %**	***AgS* %**	***Ksat* cm h^{-1}**
SS	SD1	AS	1.41	43.3	26.5	14.7	11.8	79.4	2.11^{acd}

		FS	1.40	44.5	25.5	13.7	11.8	84.2	3.23
		PS	1.40	43.5	33.3	17.0	16.3	86.7	15.89
	SD2	AS	1.30^{A}	49.5^{A}	28.0	14.4	13.6	71.3	3.04^{bd}
		FS	1.52^{B}	40.0^{B}	24.7	12.3	12.5	78.0	1.96^{c}
		PS	1.46	42.0^{B}	26.4	15.2	11.2	77.7	3.95^{d}
CS	SD1	AS	1.49^{a}	40.3	24.9	14.3	10.7	70.1	2.21
		FS	1.51^{a}	40.5	24.3	12.9	11.3	83.4	8.75
		PS	1.37^{b}	45.0	31.4	17.2	14.2^{A}	87.0	4.07
	SD2	AS	1.52	39.5	26.1	14.0	12.1	61.0	3.56
		FS	1.53	41.3	23.3	12.1	11.2	77.2	8.58
		PS	1.56	39.0	27.2	17.2	10.0^{B}	76.7	3.84

ST = Sampling type; SS = Simple sampling; CS= Composite sampling; SD = Sample depth; LUS = Land-use system; AS = Agricultural system; FS= Forest system; PS = Pasture or livestock systems; *BD* = Bulk density; *TP* = Total porosity; *FC* = Field capacity; *PWP* = Permanent wilting point; *UH* = Usable humidity; *AgS* = Aggregate stability; *Ksat* = Saturated hydraulic conductivity. Mean values with different capital letters in the same column indicate significant difference with regard to the *ANOVA* (Tukey*, α*=0.05), and means with different low-case letters in the same column indicate significant difference with regard to the ART-*ANOVA* (pairwise comparison, *α* = 0.05).

In the case of the *Ksat*, the effect of significance in the interaction systems with depths (LUS*SD) would be complicated to examine separately, because it is not additive; that is, the effect of the agricultural, pasture or forest systems on Ksat does not seem to be the same across the two sampling depths (Lyman and Longnecker, 2001). The pairwise comparisons test showed significant differences in the means of the agricultural system between the shallow (SD1) and subsurface (SD2) depths, with 2.11 and 3.04 cm h^{-1}, respectively, as well as in the mean values for the agricultural system and the pasture system, of 3.04 and 3.95 cm h^{-1}, respectively. In the composite sampling, the results of the ART-*ANOVA* did not indicate significant differences for either one of the factors or for their interaction (Table 3).

Table 3 shows that the variables *BD*, *TP*, and *UH* exhibited significant differences (P<0.05), with Tukey's test. For the *BD*, simple sampling showed significant differences in the mean values in the forest system (FS) and the agricultural system (AS) at the subsurface depth (SD2), of 1.52 and 1.30 Mg m^{-3}, respectively. For the *TP* in the simple sample, significant differences were obtained between the mean values for the AS, of 49.5 % and for the FS, of 40.0 %, as well as between the mean values for the AS, of 49.5 %, and for the PS, of 42.0 % at SD2. For the *UH*, Tukey's test showed significant differences between the mean value for the PS at SD1 and the mean value for the PS at SD2, with 14.2 % and 10.0 %, respectively. For the FC and PWP with the CS, Tukey's test (P<0.05) showed that the PS was statistically superior to the other two systems (Table 4).

Table 4. Mean values and Tukey test for the effect of land use systems, sampling depths and their interaction.

Sampling type	**Factor**		***BD* Mg m^{-3}**	***TP* %**	***FC* %**	***PWP* %**	***UH* %**	***AgS* %**	***Ksat* cm h^{-1}**
SS	LUS	AS	1.35	46.4	27.2^{a}	14.6^{a}	12.7^{a}	75.4^{a}	2.58
		FS	1.46	42.3	25.1^{a}	13.0^{a}	12.2^{a}	81.1^{ab}	2.59

		PS	1.43	42.8	29.8^{a}	16.1^{a}	13.7^{a}	82.2^{b}	9.92
	SD	SD1	1.40	43.8	28.4^{a}	15.1^{a}	13.3^{a}	83.5^{a}	7.08
		SD2	1.42	43.8	26.3^{a}	13.9^{a}	12.4^{a}	75.7^{b}	2.98
CS	LUS	AS	1.50	39.9^{a}	25.5^{a}	14.1^{a}	11.4	65.5^{a}	2.89^{a}
		FS	1.52	40.9^{a}	23.8^{a}	12.5^{a}	11.3	80.3^{b}	8.67^{a}
		PS	1.47	42.0^{a}	29.3^{b}	17.2^{b}	12.1	81.9^{b}	3.96^{a}
	SD	SD1	1.46	41.9^{a}	26.9^{a}	14.8^{a}	12.1	80.2^{a}	5.01^{a}
		SD2	1.53	39.9^{a}	25.5^{a}	14.4^{a}	11.1	71.6^{b}	5.33^{a}
SS	LUS*SD	p-value	0.02	<0.01	ns	ns	ns	ns	0.04
CS	LUS*SD	p-value	0.04	ns	ns	ns	0.01	ns	ns

SS = Simple sampling; CS = Composite sampling; LUS = Land-use system; SP = Sampling depths; AS = Agricultural system; FS = Forest system; PS = Pasture system; *BD* = Bulk density; *TP* = Total porosity; *FC* = Field capacity; *PWP* = Permanent wilting point; *UH* = Usable humidity; *AgS* = Aggregate stability; *Ksat* = Saturated hydraulic conductivity. Means with different letters in the exponent are statistically different (P<0.05).

For aggregate stability (*AgS*), the Tukey test with the SS exhibited significantly lower values for the AS than for the PS, but the same as for the FS. Tukey's test in the CS showed that the *AgS* was significantly lower in the AS than in the other two systems. The *AgS* at SD1 was significantly higher than at SD2 for both sampling types (Table 4).

Mean values

Table 4 shows that the mean values for bulk density (*BD*) in the three land-use systems and at the two depths were very similar in both sampling methods (1.4 and 1.5 Mg m^{-3}). When comparing between different soils subjected to different management practices, Soleimani *et al.* (2019) cites higher *BD* values in soils with natural forest cover and in soils used for agriculture; the same condition is registered as depth increases. These results are not congruent with the values obtained for *BD* in the present investigation, in which a homogeneous behavior was obtained; therefore, it is not possible to determine which land-use system is the best.

For total porosity (*TP*), the mean values in the three systems and the two depths were higher with simple sampling than when using composite sampling. The mean values for *TP* in the FS, the AS, and the PS are less than 50 %; this is a typical value for cultivated soils (Weil and Brady, 2017). Likewise, the values of the present study are lower than those recorded for soils with fine textures and high organic matter values. Haghighi *et al.* (2010) indicate significant differences for *TP* between the two depths when comparing soils with agricultural management and pasture, with the latter corresponding to the higher value, which they attribute to the large proportion of roots present in pasture; however, as Volverás-Mambuscay *et al.* (2016) point out, agricultural implements such as plowing increase total porosity by breaking the soil structure, which is why higher values are obtained in the short term as in this study. As time goes by, *TP* tends to decrease, and its records are much lower than those existing in systems with natural vegetation, as noted by Sustaita-Rivera *et al.* (2000).

Given that a high porosity favors more water entry into the system, with simple sampling, the agricultural system was the best, followed by forestry and pasture, with similar values. In the case of composite sampling, the most important system was pasture, followed by forestry and, finally, agriculture.

For field capacity (*FC*) in general, the mean values in the three systems and at the two depths were higher with the use of SS compared to that of CS; the highest difference between the values was about five percentage points. In general, soils were heterogeneous in terms of *FC*, with a lower value in the FS due to the higher sand content. Hillel (1998) documents that field capacity tends to be lower in soils with a higher proportion of sands, with clays such as kaolinite and with low organic matter contents. Because a high value of *FC* is better, since it favors a higher usable moisture in the system. In the present study and with the two sampling methods tested (SS and CS), the best system was the pasture system, followed by the agricultural system and, finally, by the forestry system.

For the overall permanent wilting point (*PWP*), the mean values in the three land use systems and the two SD were more similar with the use of SS compared to that of CS, although the largest difference amounted to approximately five percentage points. In relation to the *PWP*, homogeneous soils were observed, with a deviation in the pasture, whose value was higher, while the forest had the lowest value due to the lower clay content. According to Weil and Brady (2017), the *PWP* increases in direct proportion to the amount of clay present in the soil. Since a high *PWP* value is conducive to a higher water retention force in the system, for both SS and CS. The best system was the PS followed by the AS and, lastly, the FS.

In the case of usable moisture (*UH*), it was observed, in general, that the mean values in the three systems and the two SD were higher with the SS, although the maximum difference between the values was approximately one percentage point. In terms of *UH*, the soils were homogeneous, with a lower value for the FS due to a lower clay content and a higher sand content. Ortiz (2010) and Kirkham (2014) indicate that organic matter concentrations and soil texture have a very important effect on water availability, since a high *UH* value favors a higher available moisture for plants. The best system was the PS, followed by the AS and, finally, the FS; this is consistent with what was indicated in previous paragraphs for the *FC* and *PWP* values.

Regarding aggregate stability (*AgS*), its mean records in the three land use systems and at the two SD were higher with the SS, the largest difference between the values being over 16 percentage points. In general, the soils are heterogeneous in terms of the aggregate stability, with a deviation in the *AgS* due to the mechanical practices carried out in this system. According to Sustaita-Rivera *et al.* (2000), mechanized practices cause the aggregates to disintegrate, resulting in a greater loss of organic matter, which has an impact on the aggregate itself. For their part, Weil and Brady (2017) report that in very humid regions, high *AgS* values may be due to the action of inorganic components, such as iron oxides, which favor the aggregation of soil particles. Abiven *et al.* (2009) cite texture, clay, exchangeable cations, aluminum oxides, iron oxides and soil organic matter as the main properties influencing the *AgS*. Since a high *AgS* corresponds to a lower dispersion of aggregates and, therefore, to a higher water input to the system, in the two types of sampling analyzed, the best system was the PS, followed by the FS and, finally, the AS.

With respect to saturated hydraulic conductivity (*Ksat*), in general, the mean values in the three land-use systems and the two sampling depths (SD) were higher when sampling was applied; the highest difference between the two types of sampling was greater than seven percentage points. Soils were heterogeneous in terms of *Ksat* with a deviation in the pasture and forest systems for SS and CS, respectively. This is in agreement with the values obtained in the AS, since they were better in these systems and suggest a better structural stability.

Figueroa *et al.* (2018) indicate very low *Ksat* values in agricultural soils and moderately high to low *Ksat* values in pastures; these results are consistent with those of the present study. Kumar *et al*. (2017) the records for *Ksat* are higher for soils with agricultural management, in relation to those with forest use; in the case of the research documented herein, both land use systems had very similar *Ksat* values. Furthermore, Kumar *et al*. (2017) cite that the variables bulk density and percentages of clay and sand are responsible for the differences in *Ksat* observed in the different land-use systems. This is because a high *Ksat* favors the entry of larger amounts of water into the system and reduces runoff. With simple sampling, the best system was the pasture, followed by forestry and finally agriculture; while, for composite sampling, the outstanding system was the FS, followed by the PS and the AS.

Conclusions

The use of simple and composite soil sampling does not affect compliance with the assumptions of normality of data or homoscedasticity of variances of the physical variables, with the exception of bulk density and total porosity, whose results are contrasting. Sampling methods influence the determination of the significance of the effects of land-use systems and sampling depths, as they affect the values of the variables studied, as well as the interaction effects.

The forest, agricultural and pasture land-use systems have statistically significant effects on the field capacity and permanent wilting point, when composite sampling is used, and on the aggregate stability for both types of sampling. The latter is the only variable with statistically significant differences for the two sampling depths, with the highest mean value corresponding to the shallow depth with the two types of sampling. The pasture system, in comparison with the agricultural and forest systems, exhibits the most convenient records of the evaluated soil physical variables, from the agronomic point of view.

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Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Jorge Luis Núñez Peñaloza: sampling, sample preparation, data systematization, and discussion of results; David Cristóbal Acevedo: review of the laboratory test results; Elizabeth Hernández-Acosta: drafting and discussion of the results; and Antonio Villanueva Morales: statistical analysis.

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