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Research article

Soil physicochemical properties change by age of the oil palm crop

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A R T I C L E I N F O

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Soil fertility

A B S T R A C T

For decades there have been controversies related to the changes generated by oil palm plantations in the physicochemical properties of the soil, soil biota, and ecological interactions. Therefore, the present investigation evaluated root diameter and biomass at three ages of oil palm cultivation. Besides, we evaluated the effect of the ages on the physicochemical parameters of the soil in comparison with pasture plots. To know the diameter, fresh, and dry biomass of roots, soil sampling was carried out around the oil palm (3-, 5-, and 15-years-old) at distances of 1, 2, and 3 m from the trunk plant. Also, to know the changes in the properties of the soil, the sampling was carried out randomly in the same plots and the pasture plot (control). The results showed that both the diameter and the fresh and dry root biomass increased in 15-year-old plantations compared with 3- and 5-year-old. In addition, correlation analysis and principal component analysis indicated that the parameters evaluated are associated with the adult age of the oil palm. Also, the results of soil physicochemical showed that low soil fertility was associated with an increase in the age of the palm.

1. Introduction

The reports indicate that the African palm (*Elaeis guineensis* Jacq.) has covered an approximate area of 28 million hectares in the world, standing out among plant oil as the main crop that contributes to oil production [1]. However, institutions, research centers and various organizations, express concern expansion of oil palms in the decline of native habitats, the diversity of plants, animals, and their effects on the physicochemical properties of the soil [2,3]. Investigations suggests that the oil palm contributes to the emission of greenhouse gases, such as CO_2, CH_4, and N_2O [4]. The emissions are more frequent after the conversion of forests to plantations of oil palm and in plantations of 15-years-old [5,6] Also, researchers worldwide affirm that not a sustainable management in oil palm

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cultivation due to the null integrating of friendly environmental practices, minimizing the biological impact, and ecological of the soil [7].

Apart from this, to improve the physicochemical properties of the soil, proposals have been made to reduce the impact on biodiversity, identify obstacles and create initiatives that positively affect soil health and ecological relationships caused by the increase in the area planted with oil palms [8,9]. In fact, exist little information on the effect of the physicochemical and biological properties of the soil caused by oil palm [10]. In this sense, have been evaluated the physicochemical and biological parameters to determine the soil quality in the agriculture and forest systems, including industrial crops [10].

Studies suggest that the association of crops with oil palm is complicated since the canopy cover transmits little light to the soil surface, which makes it impossible for other commercial plants to grow and develop [11]. In addition, roots become entwined, causing soil compaction, nutrient competition, and strangulation of the crop roots [12–14]. However, it has been reported that oil palm included in an agroforestry system improves the physicochemical and biological properties of the soil, reduces carbon loss, and increases family income, among others [15]. Studies suggest that management practices applied to palm cultivation, such as the incorporation of crop residues (leaves, empty fruit clusters [EFB]), biofertilizers, low doses of fertilizers, cover crops, and vehicle reduction, among others, can be achieve a sustainable [8,9,16].

In crops palm, within the root architecture, cylindrical root primary with a diameter in the range of 5 to 10 mm predominate [17, 18], originating at the base of the trunk and extending horizontally or descending at different angles towards the soil [17]. Reports have shown that the diameter of the primary roots influences soil compaction and becomes increasingly critical due to the constant weight of the tractor used in the plots [19,20]. However, by nature, the roots become intertwined and generate soil compaction that hence forth in increasing the bulk density of the soil [19]. Instead, studies have shown that differences in the ages of oil palm plots cause changes in soil properties and marked differences in the soil degradation [21]. For example, Guillaume et al. [22] reported a lower carbon content, lower nitrogen, and higher bulk density under oil palms compared with under rubber trees. The authors suggest that poor palm management leads to soil degradation, highlighting that the bulk density of the soil increases in older plantations due to the compaction of the roots and a high capacity for absorbing water and nutrients in the soil compared with rubber plantations. Other studies have shown a decline in soil organic carbon in palm plantations after a land-use change (previously forest areas), with a

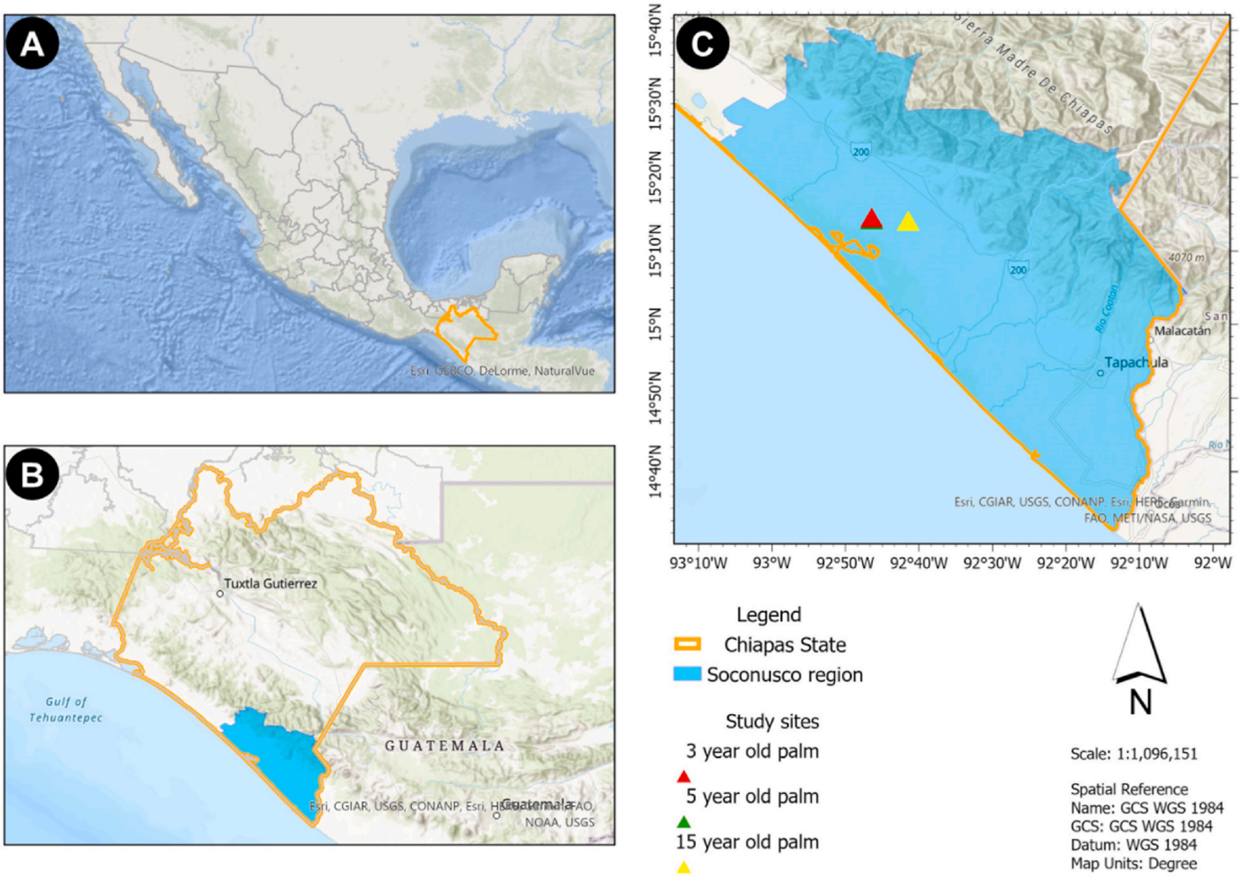

Fig. 1. Studies sites, located in Acapetahua, Chiapas, México. (**A**) Represents the national territory of Mexico, (**B**) the state of Chiapas, and (**C**) the Soconusco region. The triangles in red, yellow, and green below the red are the sampling sites in the municipality of Acapetahua. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

decrease as plantations age [5,23]. Therefore, Bessou et al. [10] argue that many palm plantations in the world have been poorly managed without improving the fertility and biodiversity of the soil ecosystem. Although, exist information reported on decreased biodiversity, change in land use, and other ecological aspects associated with the expansion of oil palm, as far as is known, few studies address the effects of physicochemical and biological of soil. Indeed, in a search carried out in the "Web of Science" database (2012–2022), in the topics section, it was found at least 67 articles using the keywords oil palm, soil degradation, fertility, and soil erosion. These data highlight the importance that should be given to ecological and environmental research generated by the agronomic management of palm. Consequently, based on the controversies of effects caused by oil palm on the physicochemical and biological properties and in the ecological aspects of the soil [24], we hypothesize that the age of the palm causes changes in the soil's physicochemical properties.

2. Materials y methods

2.1. Study site and vegetal material

Soil and roots sampling were taken from different ages of oil palm and soil samples from a pasture plot in three localities of Acapetahua, Chiapas, Mexico, were collected (Fig. 1). Table 1 shows details of the soil series and the locations of the plots. The sampling locations correspond to a tropical climate with two marked stations (a dry period, from November to June; rainy period, July to October). The soil was sampling at the beginning of the rainy season, July 2019. The soil was classified as Ferralic Xanthic Dystric Cambisol (Arenic) (IUSS Working Group, WRB, 2022) [25].

Material planted corresponds to the commercial variety 'Tenera', for the three ages of oil palm, coming from the group 'Deli × La Me'. The planting design had a in the form of an equilateral triangle staggered (143 palms ha^{-1}). In the three palm plots, it was carried out weed control, foliar fertilization twice a year (incoming and outgoing rains), and pruning every 15 days, by the owners, at the harvest time.

2.2. Sampling method

2.2.1. Roots and soil sampling

In each plot of 3-, 5-, and 15-years-old, randomly were selected oil palms ($n = 6$). For each palm tree, were delimited three circumferences at 1, 2, and 3 m away of the base of the tree stem, and at each point of intersection, sampling (monolith of 40 × 40 × 20 cm), obtaining 12 samples per plant was carried out (Fig. 2A–D). Each soil sample was sieved with a 2-mm mesh to obtain the root. Subsequently, the diameter roots primary, and fresh and dry root biomass were measured. We used the monolithic method, which is better than the auger method. Even though it is labor-intensive, the results are reliable [26]. Regardless of the sampling explained above, in order to know the physicochemical properties of the soil concerning the age of oil palm, we followed the methodology of Salgado-García et al. [27] We sampled the three ages of palm plantations and the pasture plot (n = 3, for each plot). At each point (one replica), three samples (35 × 35 × 20 cm monolith) within a radius of 10-m were taken. A sample soil composed of 2 kg of each treatment was obtained after homogenizing [27]. The soil properties evaluated were pH (by water potentiometry, [1:2.5]); cation exchange capacity (CEC), bulk density (Bd), organic matter (OM) using Walkley and Black method; total nitrogen (N_{total}) by the Kjeldahl method; sulfur (S), phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), and boron (B) quantified by spectrophotometry. All analyzes were performed as proposed by the Official Mexican Standard methods [28].

2.3. Statistical analysis

The effect of the plantation ages, the distance concerning the palm's trunk, and orientation (cardinal points) on the density and biomass of roots were analyzed. Moreover, in order to evaluate the effect of the age of the plantation on the physicochemical properties of the soil was performed a completely randomized design. In both cases, the procedure of generalized linear model (GLM) was used ($p \leq 0.05$). When the statistics indicated differences between plots, the comparison of the means test was used according to Tukey's HSD test at a 95% confidence level. To begin, our data was analyzed by the normality criteria (Shapiro test) and homoscedasticity (Bartlett or Levene's tests), it was used the statistical program Minitab (version 18.0).

Apart from this, in order to know the relationship between root diameter at different ages of the palm and fresh and dry biomass

Table 1
Locality name, geographic location, altitude, soil texture, precipitation, and age of oil palm plantations in the study.

Location (Acapetahua, Chiapas, Mexico)	Geographic location	Above mean sea level (m)	Soil texture	Average annual precipitation (mm)	Age of oil palm plantations (year)
Barrio Nuevo	15°14′19″ N 92°41′28″ W	21		2,300	15
Las Garzas (Site 1)	15°14′31″ N 92°46′26″ W	12	Sandy loam		5
Las Garzas (Site 2)	15°14′47″ N 92°46′26″ W	12			3

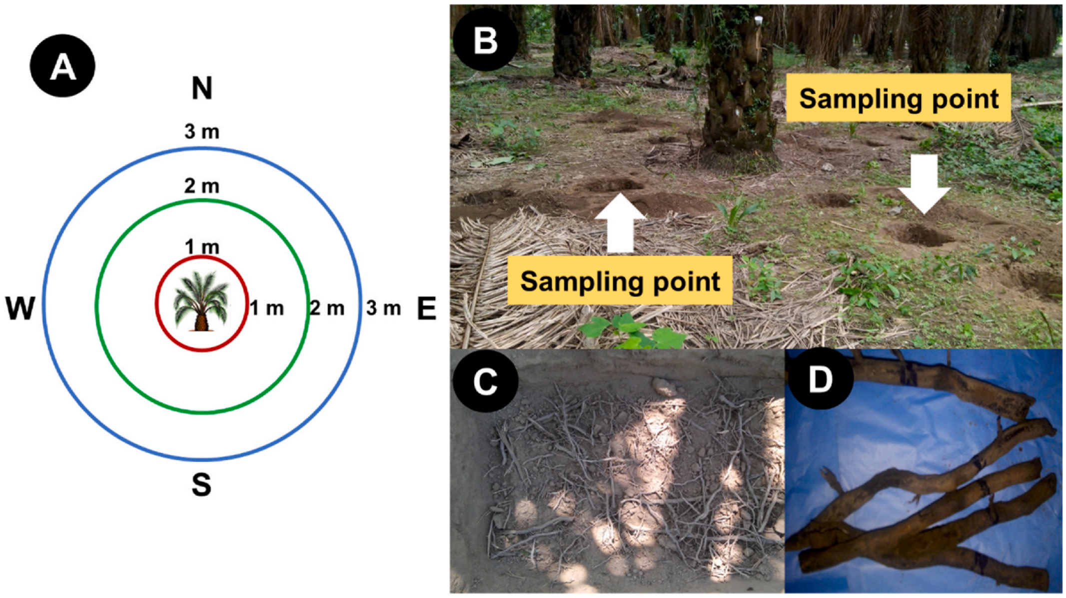

Fig. 2. **(A)** shows the sampling method carried out at the cardinal points at 1, 2, and 3 m from the trunk of the plant. Although it only shows the example in two cardinal points, the sampling was carried out in the North, South, East, and West. For each plant, 12 samples were taken, **(B)** blank arrows point to sampling points, **(C)** corresponds to a 40 × 40 × 20 monolith with the roots found for that sampling point, and **(D)** corresponds to primary roots after sampling and diameter measurement.

was calculated by a Pearson correlation coefficient with a threshold value of $p \leq 0.05$. Also, to clarify the relationship between oil palm ages, root diameter, fresh biomass, and dry biomass, a principal component analysis (PCA) was performed with Minitab (ver. 18.0) and PAST (ver. 4.09) software.

3. Results and discussion

3.1. Diameter, fresh, and dry weight of the roots

As far as the analysis of variance is concerned, the results showed significant differences between the plots of different ages, with the 15-year-old plot showing the highest values in the variable as roots diameter (Fc = 263.98, df = 2, p = 0.0001, Fig. 3). In regard to the orientation (Fc = 0.69, df = 3, p = 0.560) and distance factor (Fc = 0.37, df = 2, p = 0.694), not significant differences were found. Further analysis of variance results including interactions are shown in Table 2. Although it would be logical to assume that the age of the plant could influence the diameter of the roots, our results showed that the distance of the palm trunk base to 1-, 2-, and 3-m had no effect on the diameter of the primary roots. Jourdan and Rey [29] found that the branching of horizontal and vertical roots in palms (between 3 and 20 years old) was constant, showed a relationship between the meters of branching and the root diameter in the adult

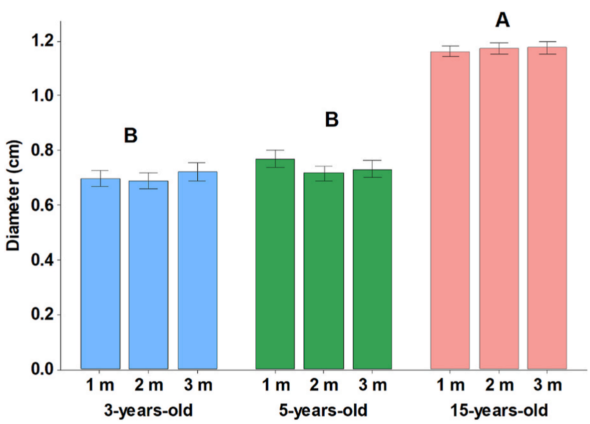

Fig. 3. Root diameter in different ages of oil palm plot. Different capital letters indicate significant differences between plots of oil palms. Data points in each vertical bar are presented as means (± standard error, $n = 6$).

Table 2
Summary of the analysis of variance showing the effect of plant age, orientation, and sampling distance from the base of the trunk on the parameter's diameter, dry, and fresh root biomass. The lowercase letter ([a]) indicates a significant difference ($p \leq 0.05$). Values represent means (±standard error, $n = 6$).

Source	Df	Diameter		Fresh biomass		Dry biomass	
		Fc	P value	Fc	P value	Fc	P value
Age palm	2	263.98	**0.000**[a]	567.21	**0.000**[a]	104.86	**0.000**[a]
Orientation	3	0.69	0.560	0.49	0.690	0.35	0.790
Distance	2	0.37	0.694	2.39	0.094	1.05	0.352
Age palm × Orientation	6	0.45	0.847	1.00	0.428	0.47	0.827
Age palm × Distance	4	0.51	0.730	2.17	0.074	1.06	0.376
Orientation × Distance	6	0.80	0.574	1.32	0.250	0.63	0.704
Error	192						
Total	215						

phase. In addition, they point out that horizontal primary roots grow several meters with a diameter between 5.0- and 7.0-mm. Similar data were found in this work, *i.e.*, roots between 7.0- and 7.3-mm were found for the age of 3- and 5-years, respectively; meanwhile at age 15-years-old, the average diameter was 1.17 cm. Other authors report similar data on the primary root diameters such as Gloria et al. [30]. The variation in growth and root diameter is still being investigated, with some reports suggesting that plantations around the world have been grown in different types of soil and weather, so the size and diameter of the roots would be varied [18]. For instance, differences were demonstrated in horizontal and vertical distribution at two palm ages (with a difference of 4-years) on Spodosol versus Inceptisol soils, where in the first soil type, roots spread at the same distance (6.5 m), but with differences in depth of 30 cm. And for Inceptisol soils, the difference in depth was higher, 1 m. Therefore, the age of the crop and the type of soil determine the architecture and diameter of the roots [18].

Regarding root biomass, the statistical analysis indicated significant differences between the ages of the palm, both for fresh biomass ($Fc = 567.21$, $df = 2$, $p = 0.0001$) and for dry biomass ($Fc = 104.86$, $df = 2$, $p = 0.0001$), highlighting that the biomass increases with the age of the plantation (Figs. 4 and 5). Concerning the distance from the trunk of the palm at 1-, 2-, and 3-m to the outside, not significant differences were found in fresh ($Fc = 2.39$, $df = 2$, $p = 0.094$) and dry biomass ($Fc = 1.05$, $df = 2$, $p = 0.352$), respectively. Likewise, not significant difference was found regarding the orientation in fresh ($Fc = 0.49$, $df = 3$, $p = 0.690$) and dry biomass ($Fc = 0.35$, $df = 3$, $p = 0.790$), respectively (Table 2). Therefore, our results suggest that the biomass presents a constant growth from the trunk base of the palm up to 3-m away. These results may have a logical sense compared with the results reported by Reyes et al. [31]. The authors found a diameter and homogeneous horizontal growth in distant roots from the trunk base of the palm up to 50 cm in the first year, 1.5 m in the second year, and 2.0 m in the third year. In addition, other results show evidence that after a distance of 3 m, the roots continue to grow. Intara et al. [17] revealed that the growth of the roots can grow up to 6 m horizontally, highlighting that the primary roots serve to support the plant, which predominates at a depth of 40 cm. However, soil conditions and texture are the most important factors in root growth. Interestingly, the soil texture in our study in the three oil palm plots was sandy loam. Therefore, we suggest that density, dry biomass and root distribution depend on the age of the palm [32]. Despite the various studies that have estimated biomass and root distribution in oil palm plantations, the authors point out that this parameter remains difficult and slow to determine [33]. They demonstrated that the OM and nutrients affect the biomass and the length of roots and also suggested that the reuse of leaves after pruning promotes the formation of primary roots up to a depth of 20 cm [33].

The analysis of the correlation between the fresh biomass of the root, the dry biomass of the root, and the diameter of the root at three ages of the palms, showed that the fresh biomass of the root and the dry biomass of the oil palms at 3 and 15 years of age had a significant correlation ($r^2 = 0.68$, $p < 0.0001$ and $r^2 = 0.61$, $p < 0.0001$, respectively). Additionally, to further clarification of the

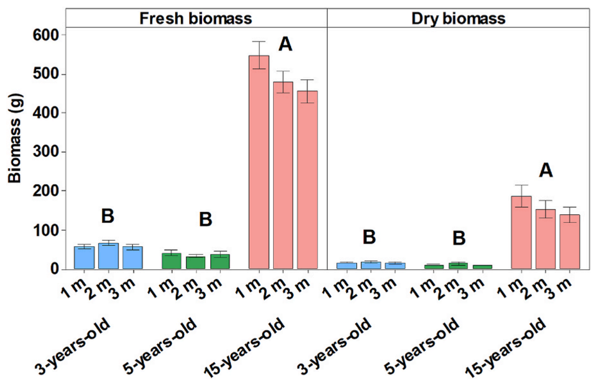

Fig. 4. Biomass in different ages of oil palm plot. Different capital letters indicate significant differences between plots of oil palms. Data points in each vertical bar are presented as means (± standard error, $n = 6$).

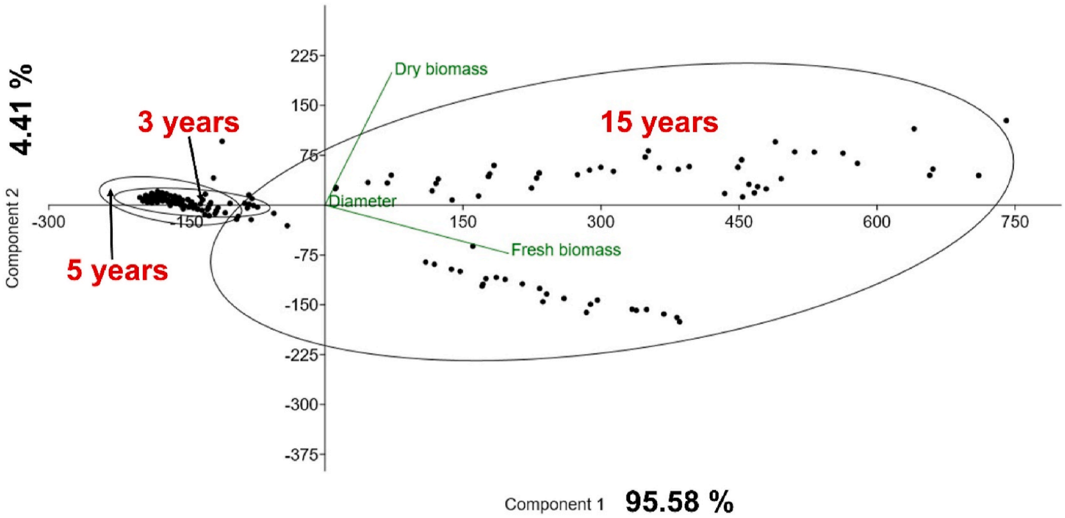

Fig. 5. Principal components analysis that explains the variance and the participation of the age of the palm in the first two components and its effect on the diameter and biomass of the oil palm roots.

relationship between the parameters studied, it was explained in 95.6% by the first principal component, while the second component was 4.41% (Fig. 5). Also in the scatterplot, the first principal component, where the 15-year-old plots were found in the right quadrant, had a positive relationship and at the same time was related to fresh biomass and dry biomass of roots, while the rest of the plots were in the lower left quadrant. (Fig. 5). In order to know the behavior of the root architecture (length, diameter, and biomass) in oil palm plantations, the Minirhizotron (equipment & software), 2-D scanning, or tomography could be use, which, compared with collecting soil samples, these technologies might save time, cost, and labor.

3.2. Effect of the physicochemical properties of the soil by oil palm cultivated in plots at a different age

Most of the parameters evaluated were significantly different between treatments (Table 3). Soil physical parameters: pH values appeared not to be affected by treatments ($p \leq 0.05$). The OM was higher in 3-year-old oil palm than in the 5- and 15-year-old and lightly different in grass plot ($p \leq 0.05$). Soil Bd was significantly higher in 15- and 5-year-old palm plots than in the 3-year palm plot and the grass plot ($p \leq 0.05$).

With regard to soil chemical properties, the N_{total} was statistically similar in all the treatments (including control treatment) (Table 3). However, the phosphorus content of the 3- and 5-year-old oil palm was significantly higher than that of the palm of 15-year-old and the grass plot ($p \leq 0.05$). The K and Mg were significantly higher grass plot, 3- and 5-year oil palm than in the 15-year palm ($p \leq 0.05$). The Cu, S, Mn, and Zn were significantly higher in 3-year-old palm than in rest plots ($p \leq 0.05$). Finally, only the Ca and B were higher in the 15-year-plot than in the rest of the plots ($p \leq 0.05$). We observed that as the palm grows, the root system gains space in the

Table 3
Soil properties at different stages of oil palm (*Elaeis guineensis* Jacq.) in the municipality of Acapetahua, Chiapas, México.

Variables	Oil palm plantation ages			Grass
	3-years-old	5-years-old	15-years-old	
pH	6.66 ± 0.08 a[a]	6.43 ± 0.20 a	6.66 ± 0.13 a	6.48 ± 0.03 a
Bd (g cm^{-3})	0.95 ± 0.01 c	1.01 ± 0.01 b	1.11 ± 0.00 a	0.96 ± 0.00 c
OM (%)	2.96 ± 0.08 a	1.70 ± 0.02 c	0.99 ± 0.00 d	2.73 ± 0.00 b
CEC (meq 100 g^{-1})	9.88 ± 0.37 a	6.62 ± 0.06 c	6.57 ± 0.20 c	7.55 ± 0.01 b
N_{total} (%)	0.17 ± 0.00 a	0.14 ± 0.00 a	0.40 ± 0.29 a	0.16 ± 0.00 a
S (mg kg^{-1})	21.8 ± 0.23 a	18.9 ± 0.33 b	11.2 ± 0.00 c	18.9 ± 0.33 b
P (mg kg^{-1})	24.1 ± 0.00 a	21.7 ± 0.00 b	10.3 ± 0.00 d	16.7 ± 0.37 c
Ca (meq 100 g^{-1})	31.8 ± 13.6 b	43.2 ± 0.35 b	98.5 ± 0.21 a	34.7 ± 0.26 b
Mg (meq 100 g^{-1})	1.85 ± 0.00 a	1.44 ± 0.05 b	1.27 ± 0.00 b	1.87 ± 0.05 a
K (meq 100 g^{-1})	0.26 ± 0.01 a	0.28 ± 0.00 a	0.13 ± 0.01 b	0.27 ± 0.00 a
Fe (mg kg^{-1})	68.9 ± 0.49 a	55.0 ± 0.57 ab	18.0 ± 7.75 c	37.7 ± 0.38 b
Cu (mg kg^{-1})	3.96 ± 0.01 a	3.22 ± 0.00 c	3.55 ± 0.05 b	3.64 ± 0.00 b
Mn (mg kg^{-1})	3.56 ± 0.00 a	2.63 ± 0.07 b	1.86 ± 0.00 d	3.13 ± 0.00 b
Zn (mg kg^{-1})	3.24 ± 0.00 a	1.66 ± 0.00 c	0.87 ± 0.01 d	2.56 ± 0.00 b
B (mg kg^{-1})	3.13 ± 0.00 b	1.80 ± 0.05 d	4.35 ± 0.09 a	2.55 ± 0.00 c

[a] Different letters on the same line indicate significant difference between plots (Tukey, $p \leq 0.05$). Values represent means (±standard error, n = 3).

soil and consequently increases the absorption of nutrients. This could be more critical since if the null practice or poor management of soil fertilization, whether mineral or organic, persists, the oil palm will continue to absorb nutrients to such a degree that the soil might become somewhat infertile. In addition to this, as it knows the palm plot becomes adult and influences the soil properties, such as was stated by Basuki et al. [34], they found that the older the palm (3, 5, 7, 9, 14, and 16 years old) at four soil depths, observed un decreased in SOC, pH in water, and pH in KCl. In our study, a statistical difference was observed between palm ages for the pH parameter. The values oscillated between pH 6.48 and 6.66, with a mean of 6.56. ($p \leq 0.05$; Table 3). Both palms and grass plots had a typically neutral to slightly acid pH (the soil texture for all the evaluated plots was sandy loam). Okon et al. [35], compared with plots from 1978, 1990, and 2005, and reported significant differences in porosity, pH, OM, SOC, N_{total}, P and K available, and moisture content. For our study, we suggest that the high OM values in a young 3-year-old plot are due to the low intensity of agronomic work compared with the rest of the plots. The contrast of the results of the previous studies made sense since the types of soils, sampling depth, and climatic conditions were not the same. For instance, Gandaseca et al. [36] shown a contradictory result, they found that regardless of the age difference (2-3- years-old compared with 15-years-old), the total carbon, OM, and EC were statistically similar, but the amount of N, P, K, C/N, and C/P ratios were significantly higher between three areas weather (2-, 3-years-old, and mature oil palm plantation). Also, Nelson et al. [37] found that after 25 years of conversion from grasslands to oil palm, there was a decrease in the soil pH and exchangeable Mg, but without changes in C content. In addition, the results cause controversy because the sampled sites correspond to the same texture. These results differ from our study since the soil type in the three evaluated localities corresponds to the sandy loam class.

Regarding the N content, we found that the N_{total} was similar in all plots, including control treatment. The above suggests that the variations in indigenous soil N supply, N rates, application methods, organic or mineral fertilizer, and other biotic and abiotic factors affect yield responses to N_{total} [38]. Therefore, sometimes it is not possible to understand the contrasting results when are compare with the palm of different ages and agricultural areas with excessive management. For instance, Behera et al. [39] reported an increase in the parameters such as pH, Ca, exchangeable Mg, and S available down to a depth of 60 cm in oil palm plots compared with intensively managed land. Besides, in 6-, 12-, and 18-years-old palm oil trees, the available P increased with the age of the plantation. However, plantation age did not change the concentrations of available N, exchangeable K, Ca, Mg, and the available S and B [39]. Another study showed that when N application and N uptake efficiency were assessed in oil palm plantations compared with a tropical forest, root N content was one third higher in the tropical forest than in the oil palm plantations. Nevertheless, the uptake efficiency was similar in both systems [40]. Both our results and those discussed previously suggest that the decrease in the content of elements in the soil is due to the need for absorption or use required by the oil palm for the formation of clusters of fresh fruit [40,41]. In this line, the present experiment showed that higher values of the elements K, Mg, Cu, S, Mn, and Zn were present in 3-year-old plots and the pastures compared to 15-year-old adult plants. It may be normal to think that the absence or poor management of monoculture systems leads to soil degradation. In previous paragraphs, we mentioned that the plots evaluated in this work received little management (adult plantations), causing a decreased soil fertility. In fact, researchers argue that excess fertilization can increase leaching processes and modify soil reserves in oil palm [42]. In this sense, it has been documented that the excessive supply of fertilizers results in high production costs and soil contamination [43]. For instance, compared with unfertilized palm plots, continuous fertilization for 10 years resulted in a decrease in soil pH, CEC, and exchangeable cations [42]. This explains the concern of researchers and environmentalists who argue that the change in land use from forest and jungle to palm plantations changes the quality of the soil, which is further degraded by the poor management of oil palm. It has been demonstrated in several investigations around the world that the oil palm causes compaction soil is practically in the absence of appropriate conservation practice [44]. Our results suggest that soil compaction increases as the palm plot matures. These results showed in Table 3, with significant differences between the cropping systems ($p \leq 0.05$). Bd was lower in the 3-year-old and pasture plots, however, higher in the 5-year-old and 15-year-old plots. In addition, these results have been reported previously, suggesting that root density and poor crop management influence compaction and consequently an increase in Bd [10]. In timber plantations such as Brazilian pine (*Araucaria angustifolia* [Bertol.] Kuntze, 1898) shown that soil Bd was related to thick and short roots [45]. Furthermore, it makes sense with the similar results found by Enaruvbe et al. [46] where revealed that the conversion of land use from rainforest to oil palm and rubber plantations showed that at a depth of 15 to 30 cm, reductions in SOC, N_{total}, and phosphorus compared with soil samples from tropical forests were observed. And also suggest that soil degradation is more severe in oil palm plantations than in rubber plantations [46]. Recently, Prawito et al. [21] suggest that proper management and improving soil SOC with the maintenance of undergrowth vegetation can achieve soil sustainability and shown the understory vegetation biomass, weight, and density decreased with the increasing age of the plantations compared with young plants of 4 years of age [21].

Palm plantations with organic management practices result in changes in soil properties. Indeed, investigations have shown positive effects [8,16]. For instance, Yeo et al. [47] reported that in plantations older than 20 years, the amounts of C, N, and OM were higher compared with plantations of 13 years old, but similar to that of secondary forests. Therefore, it is necessary to understand that natural systems such as forests, jungles, and integrated systems increase ecosystem services, unlike poorly managed monocultures. Rahman et al. [8] revealed the incorporation of cover crops after 15 years of palm establishment. Besides, the addition of EFB (26 t ha^{-1}) increased SOC and a higher yield per ha compared with unmanaged plots. Similarly, the reduced fertilizer application, mechanical weeding, and incorporation of OM resulting in an increase in the extractable organic carbon and higher the microbial activity in the soil [16]. The results presented in Table 3 clearly show that the age of the crop causes changes in the characteristics of the soil to such an extent that fertility could be reduced, thus affecting the production of fresh fruit bunches (this parameter was not evaluated in our study, but has been reported in other studies) [8].

The poor agronomic management of oil palm causes changes in the undergrowth, nutrient dynamics, and changes in biodiversity, among others [48]. In this sense, for the first time in the study region, there is clear evidence of the impact of oil palm on soil properties.

Therefore, this study contributes to the field of knowledge that oil palm requires sustainable management, which implies the diversification of management practices that help to improve soil quality, improve interactions between plant roots and microorganisms, as well as how to promote an increase in the biodiversity of the mesofauna and macrofauna of the soil [49]. Furthermore, palm oil needs to be managed holistically, as managing in one way is not considered to be comprehensive [50]. These aspects are not considered by the governments that promote the increase of the area planted with oil palm, as in the case of Mexico [51]. Studies have shown that poor management of palm plantations has led to soil degradation, water shortages and biodiversity loss [50,52]. Therefore, best management practices can reduce impacts and potentially maintain sustainable oil palm plantations.

4. Conclusions

This work shows that the increase in diameter and biomass of oil palm roots is related to the age of the crop and consequently determines soil compaction. The present study also showed that the physicochemical properties of the soil changed with the ageing of the crop. In this sense, we emphasise that good agronomic management of oil palm is essential to reduce the negative impact on the soil. Although the management practices were not evaluated in the present work, we believe that soil quality can be improved by managing the understorey with leguminous plants, thus promoting the increase of soil nitrogen. The incorporation of organic matter may also increase the soil biota and, failing that, improve the quality and integrity of the soil. Reducing the use of herbicides can be essential to achieving healthy soils. This will also reduce production costs. Finally, we suggest that producers in the study region should consider the sustainable management of agricultural practices.

Author contribution statement

Pérez-Sato, Gómez-Gutiérrez, and Pérez-Hernández: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

López-Valdez, Ayala-Niño, Soni-Guillermo and González-Graillet: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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