A new approach to the nutritional status of manganese in oil palm plants cultivated in the eastern Amazon[1]

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ABSTRACT

Little is understood about the nutritional status of manganese (Mn) in oil palm (*Elaeis guineensis* Jacq.), further research is needed to provide technological support for greater productivity, especially on the dynamics of accumulation, recycling, immobilization and export. Thus, the objective of this work was to evaluate the dynamics of accumulation, immobilization, recycling, exportation and the efficiency of Mn use in oil palm plants at different ages. The experiment was carried out in a completely randomized design, with seven treatments (plant age: 2, 3, 4, 5, 6, 7, and 8 years of planting) and four replicates. The leaflets and male inflorescence were, the vegetative and reproductive organs with the highest Mn concentration, respectively. The accumulation of this nutrient in the tree crown predominated in the stipe through all years. The bunch exported the highest amount of Mn, especially in older plants. The oil palm immobilizes and recycles, more than exports, a large amount of Mn. The Mn use efficiency is increased as a function of the age of the crops in all the oil palm organs. In conclusion, the nutritional demand of oil palm is altered as a function of age, altering the dynamics of immobilization, recycling and exportation of Mn.

Keywords: *Elaeis guineensis* Jacq.; Mn export; Mn immobilization; Mn recycling; Mn use efficiency.

INTRODUCTION

The oil palm (*Elaeis guineensis* Jacq.) is an oilseed palm that originated from Africa and is an important source of vegetable oil that is widely used in the cosmetic and biodiesel industry (Lebid & Henkes, 2015). From the economic point of view, its useful life is around 25 years, and the maximum productive potential is normally reached in the eighth year, where 25 t ha^{-1} $year^{-1}$ of bunches can be harvested, resulting in 4 to 6 t ha^{-1} $year^{-1}$ of vegetable oil (Nabun *et al.*, 2017; Cruz Filho *et al.*, 2019). When cultivated in the field, the oil palm presents two distinct stages; growth and production (Costa *et al.*, 2017).

Oil palm has excellent development in environments with high precipitation, and when in a dry environment, it can manifest low fruit and inflorescences production (Chagas *et al.*, 2019). This crop requires for its full development temperatures between 24 and 28 ºC, rainfall of 2000-2500 mm $year^{-1}$, well distributed during every month, in addition to deep and uncompacted soils (Pirker *et al.*, 2016). In the eastern Amazon, there is a predominance of Oxisols and Argisols (Gama *et al.*, 2020), with low natural fertility, high acidity, and aluminum saturation (Al), requiring adequate correction and fertilization to enable crop production (Fer-

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nandes *et al.*, 2013). It is emphasized that acidic soils may present high concentrations of Mn, with toxic potential to plants and animals (Lopes & Guilherme, 2007). Increases in the pH of acidic soils can promote the decrease of the availability of Al and Mn ions (Silva & Mendonça, 2007). Oil palm cultivation in Pará is traditionally carried out in acidic soils without pH correction which increases the availability of Mn to plants (Homma & Rebello, 2020).

Mn is a micronutrient necessary to photosynthesis and is involved in the structure, functioning, and multiplication of chloroplasts, in addition to its role in the electron transport (Vitti *et al.*, 2006). It also plays a key role in the activation of various enzymes in the shikimic acid route, leading to the biosynthesis of aromatic amino acids such as tyrosine, tryptophan, and phenylalanine, and various secondary products such as lignin and flavonoids (Wilkinson & Ohki, 1988). Also, a large amount of Mn is present in the growth areas of the plant, mainly in the palm heart, as the nutrient concentrates around meristematic tissues (Vitti *et al.*, 2006).

The nutritional needs of oil palm are large and vary widely, depending on yield, planted genotype, spacing, palm age, type and soil cover conditions, climate, and other environmental factors (Woittiez *et al.*, 2017). About the micronutrients, there are few long-term studies developed with oil palm plants, however, some reports are found in the literature (Viégas *et al.*, 2019; Viégas *et al.*, 2020; Viégas *et al.*, 2021). The evaluation of commercial oil palm nutrition in Pará pointed to Zn and Mn as the most deficient micronutrients in this palm tree (Matos *et al.*, 2016). Therefore, monitoring manganese in plant organs as a function of age is necessary due to the importance of this nutrient in several fundamental plant processes such as photosynthesis and respiration, which are affected with plant age. Therefore, the objective was to evaluate the accumulation, recycling, immobilization, exportation, and Mn efficiency use in the different organs of the oil palm plant as a function of the planting age.

MATERIAL AND METHOD

The experiment was carried out under field conditions at Agropalma S/A, located in the northeast of Pará, on the municipality of Tailândia-PA (2° 56’ 50’’ S and 48° 57’ 12’’ O). The climate in this region is Ami type (tropical rainy), according to Köppen classification, with an average annual temperature of 26.5 °C, annual rainfall of 2,400 mm, and relative air humidity of 84%. The rainfall during the experimental period was monitored using a rain gauge installed at the company Agropalma, observing rainfall of 1523, 3256, 3093, 2575, 2011, 2397 and 2293 mm year^{-1} from the first to the seven year, respectively. The average annual temperature was 26 °C and the average minimum and maximum temperatures ranged from 21 °C and 32.5 °C, respectively. The average relative humidity of the air during this period was 83%. Seven treatments (plant ages; 2, 3, 4, 5, 6, 7, and 8 years of planting) were evaluated with four replications, in a completely randomized experimental design. Four palm trees were sampled for each age, and the following components were collected: leaflets, petioles, rachis, cabbage, arrows, stipe, male inflorescences, peduncles, spikelets and fruits. The plants came from Companhia Real Agroindustrial (CRAI). The plants were grown at a spacing of 9 m, in an equilateral triangle, making a “stand” of 143 plants/ha. The legume Pueraria phaseoloides was used as ground cover throughout the CRAI plantation. The productions were collected from the third year of cultivation, reaching 1.5 t bunch/ha, in the fourth, fifth, sixth, seventh and eighth years the plants reached productions of 7.0; 9.0; 15.0; 19.0 and 20.0 t bunch/ha. Regarding fertilization, these were carried out at all ages, in which the following nutrients were applied in g plant^{-1}: in year 2 (N: 35; P_2O_5: 60; K_2O: 60; S: 24), in year 3 (N: 18; P_2O_5: 77; K_2O: 154), in year 4 (N: 56; P_2O_5: 115; K_2O: 300; Mg: 60; S: 45), in year 5 (N: 97; P_2O_5: 336; K_2O: 240; Mg: 60; S: 45), in year 6 (N: 135; P_2O_5: 470; K_2O: 335; Mg: 77; S: 58), in year 7 (N: 135; P_2O_5: 470; K_2O: 335; Mg: 102; S: 58 and H_3BO_3: 50) and year 8 (N: 160; P_2O_5: 384; K_2O: 324; Mg: 68; S: 52 and H_3BO_3: 60).

According to Rodrigues *et al.* (2005) and Santos *et al.* (2018), the soil of the experimental area is a Dystrophic Yellow Oxisol, with low natural chemical fertility, high acidity, and medium texture. During the period in which the plants were collected, soil sampling (0 - 0.3 m) also occurred. Four simple samples were collected between planting rows for each age of the plants to form a compound sample. After the soil sampling, the samples were sent to the laboratory of the Department of Soil Science of the Higher School of Agriculture “Luiz de Queiroz” for chemical characterization (Table 1). For the characterization of soil physical attributes, the analyses were carried out at the Center for Agroforestry Research of eastern Amazon and presented the following results: a) area with two-year-old plants (g kg^{-1}) 730 sand, 40 silt, and 230 clay; (b) with three years of age (g kg^{-1}) 620 sand, 160 silt, and 220 clay; (c) with four years (g kg^{-1}) of age 690 sand, 80 silt and 230 clay; (d) with five years of age (g kg^{-1}) 680 sand, 100 silt, and 220 clay; (e) with six years of age (g kg^{-1}) 590 sand, 80 silt, and 330 clay; (f) with seven years of age (g kg^{-1}) 660 sand, 100 silt, and 240 clay; (g) and at eight years of age 740 sand, 60 silt and 200 clay.

For this experiment, oil palm plants of the commercial hybrid Tenera (Dura x Psífera), aging from 2 to 8 years, and spaced in an equilateral triangle (9 x 9 m) with a total of 143 plants ha^{-1}, were used. The data on productivity and fertilization and the sources of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and sulfur (S) fertilizers used in the experiment are shown in Table 1. The fertilization of B was carried out at the seventh and eighth crops using 50 and 60 g $plant^{-1}$ of boracic acid, respectively.

Uniform, healthy, well-developed, and nourished plants, presenting good yield, and with ages of 2, 3, 4, 5, 6, 7, and 8 years from the same plot, were selected for their organs sampling for further analysis. After identification of the plants, the circumference and height of the plants were measured, with the latter being measured from the base leaf of number 33, advocated by Surre (1979) and Jacquemard (1979), which has the advantage of corresponding to the height of the mature bunch to be harvested. The sampling process consisted of separating in each plant the leaflets, petioles, stipe, rachis, palm heart, central spear, male inflorescence, peduncles, spikelets, and fruits, obtaining representative samples of each plant component and Fresh weight (FW).

The samples of the collected plant material were sent to the laboratory, where a subsample (SAM) was collected, stored in a paper bag, and dried in a forced-air circulation oven at 70 °C until it reached constant mass. Subsequently, the dry mass of the subsamples (MSSA) of the different vegetative organs collected was quantified. The FW, SAM, and MSSA data of each material were placed in the equation (DW = MSSA*FW/SAM) for the estimative of the dry weight (DW) of each plant component. The Mn in each plant component was determined by atomic absorption spectrometry, following the method described by (Malavolta *et al.*, 1997), after the dry plant tissue was milled in a Wiley mill.

The effects of the treatments were evaluated by concentration, accumulation, and export of Mn in each plant component. From the concentration of Mn in the plant tissue and dry mass values, the amounts of Mn accumulated in each of the oil palm components for each age were estimated. The immobilized amounts of Mn were obtained by adding the accumulated stipe, palm heart (palm heart), and central spear, while the recycled were from the leaflets, rachis, petioles, and inflorescences. Additionally, the Mn use efficiency was calculated, for this response variable, the use efficiency for all organs and the total plant efficiency were calculated using the methodology described by Siddiqi & Glass (1981). The data were submitted by the tests of normality and homogeneity prepositions, consequently, the results were submitted to variance analysis (F test; $p < 0.05$) and regression model adjustments through the statistical software Sisvar (Ferreira, 2011).

Table 1: Chemical characteristics of soil (0-30cm) in oil palm plantation of different ages

Plant age (years)	Chemical attributes of soil								Mineral fertilizers				
	pH	K	Ca	Mg	Al	H+Al	P	MOS	N	P_2O_5	K_2O	Mg	S
	$CaCl_2$	$mol_c\ dm^{-3}$					mg dm^{-3}	g kg^{-1}	g $plant^{-1}$				
2	4.3	0.07	0.7	0.4	0.4	3.4	4	16	35	60	60	__	24
3	4.4	0.06	0.7	0.2	0.3	2.8	6	23	18	77*	154	__	__
4	4.1	0.05	0.9	0.2	0.3	3.1	5	15	56	115	300	60	45
5	4.0	0.07	0.8	0.3	0.5	3.8	6	19	97	336	240	60	45
6	4.0	0.05	0.7	0.3	0.8	3.4	6	20	135	470	335	77	58
7	4.3	0.05	0.7	0.3	0.4	2.6	6	21	135	470	335	102	58
8	4.0	0.06	0.6	0.3	0.6	3.4	8	18	160	384	324	68	52

K, Ca, and Mg extracted with ion exchange resin; H+Al obtained by the SMP method; SB represents the sum of the basic cations; P extracted by ion exchange resin; V base saturation; MOS (soil organic mass) obtained by the colorimetric method. *Application of 500 kg ha^{-1} of phosphine (rock phosphate); Fertilizer sources of N (Urea - 45% N), P (Natural Phosphate - 33% P_2O_5 and 42% CaO), K (Potassium Chloride - 60% K_2O and 45% Cl) and Mg (Mg Sulfate - 18% Mg and 13% S).

RESULTS AND DISCUSSIONS

The Mn concentrations in the organs of the oil palm increased with the age of the plants (Figure 1). This high concentration of Mn may be related to its high availability in acid soils (Nachtigall *et al.*, 2009), which is a common environmental factor in oil palm croplands throughout Pará State (Homma & Rebello, 2020), and in the present study (Table 1). On the other hand, Singh (1984) researching the availability of Mn in the Brazilian Amazon (Pará, Amapá, and the Roraima States) found that the Yellow Oxisol is poor in Mn, different from the Yellow Red Latosol, Gleisoil, Red Nitisol that are rich in Mn.

An increasing quadratic response was observed for the Mn concentration in the vegetative organs such as leaflets, rachis, and central spear, in relation to the ages of the plants, however the maximum points were estimated above 8 years of age (Figures 1a and 1b). On the other hand, the Mn concentration in the other components responded negatively with increasing plant age (Figure 1), that is, in this case, their concentrations reduced as the plants became older. Probably, the decrease in the concentration of this nutrient in the organs is due to the fact that the oil palm plant was not able to redistribute this nutrient to other organs.

In the bunch-forming components, the fruits were the richest in Mn, while in the far east region there was a higher concentration of this micronutrient in the oil palm almonds, one of the fruit constituents, followed by peduncles and spikelets (Ng & Thamboo, 1967). In the present work, the latter two components, in general, presented the lowest levels of Mn. Compared to the results obtained by Ng & Thambo (1967), the Mn concentrations in the peduncles and spikelets were 65 and 50% lower, respectively. The concentration range of Mn in the fruit cluster components ranged from 13.75 mg kg^{-1} of Mn (peduncles) to 92.95 mg kg^{-1} of Mn (fruits) and from 4 mg kg^{-1} of Mn (pulp) to 158 mg Mn kg^{-1} (almond), obtained by the researchers, mentioned above, in Malaysia.

Confronting the Mn concentrations obtain ed with those of Ng *et al.* (1968), it is verified that, under Asiatic conditions, they were higher, from 1.3 to 3.0 times in leaflet, from 1.3 to 4 in the rachis, from 3.0 to 4.6 in the central spear, from 1.8 to 5.4 in the palm heart and 3.0 to 4.2 times higher in the stipe. These high concentrations of Mn probably occurred due to the higher concentrations of this micronutrient in the Malaysian soil. Also in Malaysia, the average Mn concentration in the soil was 11.6 mg kg^{-1} (Ng *et al.*, 1968; Zakaria & Gammon, 1979), in the Yellow Oxisol, and in the present work determined by Singh (1984), it was only 0.97 mg kg^{-1}.

According to Rodrigues *et al.* (2002), the critical level for Mn is not yet well defined, perhaps for this reason a significant variation in the concentrations of this nutrient in the different organs of the plant was observed in this study. An increase of 57% in bunch production was demonstrated in Zaire, in the oil palm crop as a consequence of the application of this micronutrient (Ferrand *et al.*, 1951). According to Rognon (1984), leaf Mn contents in the range of 58 to 86 mg kg^{-1}, proportionated a yield of 25 t $bunches^{-1}$ ha^{-1} $year^{-1}$, which was not sufficient to provide a production increase. Therefore, according to this author, 50 mg kg^{-1} seems to be sufficient for oil palm. However, to obtain a response with the application of this micronutrient, its critical concentration in the leaf would be 20 mg kg^{-1}. Symptoms of Mn deficiency in oil palm seedlings, grown in the nutrient solution, were observed by Dufourt & Quencez (1979), whose Mn content was 22 mg kg^{-1}, compared to 235 mg kg^{-1} in normal plants.

The components that presented concentrations above 50 mg kg^{-1} were the leaflets, palm heart, male inflorescences, and fruits, with the others below this content. Values below the critical level of 258 and 244 mg kg^{-1} (Matos *et al.*, 2016) are bad because it affects the economic viability of fertilizer use, as a greater amount of this element will be needed to meet the plant's needs. More recently, critical levels of 258 and 244 mg kg^{-1} of Mn were determined in the leaf 17 of young and adult plants of oil palm, respectively, cultivated under Amazonian conditions (Matos *et al.*, 2016). For Rodrigues *et al.* (2002), it is possible to find in leaf 17 of the oil palm, concentrations of Mn ranging from 80 to 1000 mg kg^{-1}. This concentration range was also observed in this study for the palm heart and fruits. According to Rognon (1984), among the micronutrients, Mn is the most subjected to variations in the leaves. Mn was identified as one of the most deficient micronutrients in commercial oil palm crops in Pará (Matos *et al.*, 2016). In a study conducted by Viégas *et al.* (2021) with palm plants in Pará State, it was observed that the concentrations of this micronutrient in the shoot (leaves) reduced from 499 to 415 mg kg^{-1} of when the phosphorus (P) doses increased. According to Matos *et al.* (2016), the critical levels of Mn in the oil palm planted in the Amazon region is 258 mg kg^{-1} of Mn for young oil palm and 244 mg kg^{-1} of Mn for adult oil palm. Considering all ages evaluated, there was variation in Mn contents in the different organs of oil palm

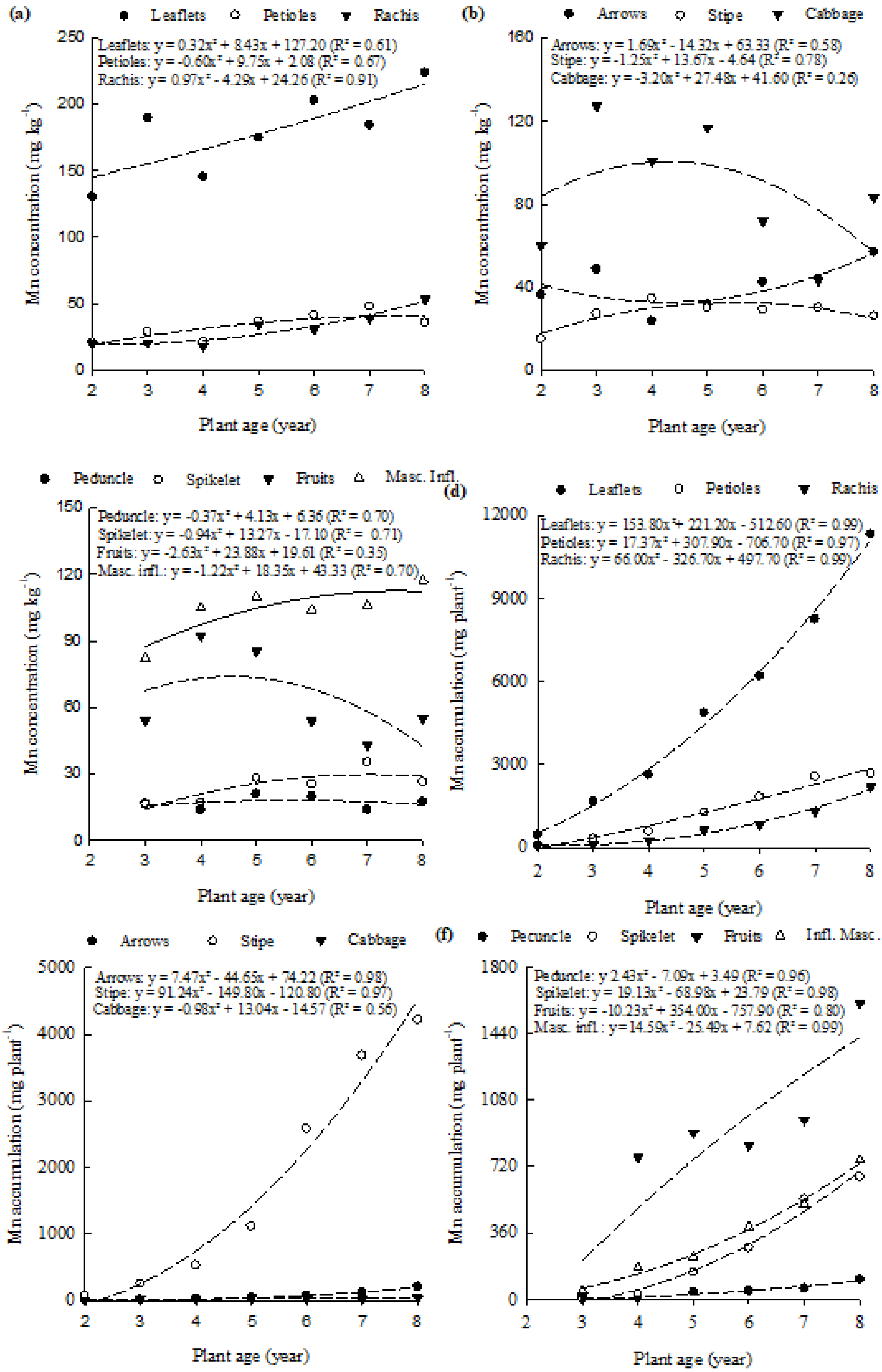

Figure 1: Mn concentration in the leaflets, petioles, and rachis (a), in the palm heart, central spear, and stipe (b), in the male inflorescences, peduncle, fruit, and spikelet (c) and Mn accumulation in the leaflets, petioles, and rachis (d), palm heart, central spear, and stipe (e), in male inflorescence, peduncle, fruit, and spikelet (f) depending on the age of the oil palm.

plants, mainly in palm heart and ráquis (194%), presenting a variation from 43.25 to 127.25 mg kg^{-1} of Mn and 18.25 to 53.62 mg kg^{-1} of Mn, respectively (Table 2). This variation demonstrates that Mn is a mobile element in the different organs of the plant, which can be considered important to maintain this element in the different organs.

On the other hand, male inflorescences showed less variation (26%) in Mn concentrations (82.0 to 103.75 mg kg^{-1} of Mn). Viégas *et al.* (2020), evaluating Cl in oil palm trees, also observed greater variation in the nutrient contents in the palm heart of the plants. According to these authors, these variations alter the metabolism of the plant and, consequently, the uptake rates of nutrients, since at the beginning of vegetative development the production is still relatively low (6 to 8 t ha^{-1} year^{-1} bunches), gradually increasing until the plants reach eight years, reaching the maximum yield of 20 to 30 t ha^{-1} year^{-1} of bunches.

The Mn accumulation in the organs indicates an increase with the age of the plants, with greater absorption occurring in the eighth year (Figure 1). The highest Mn accumulated was obtained in the leaflets, reaching, 11,314.97 mg plant^{-1} of Mn in the eighth year, corresponding to 48%. In the second place, the stipe stood out with 4,216.98 mg plant^{-1} of Mn, which in percentage terms meant 18%. The Mn accumulation in all organs was represented by ascending quadratic behavior, except for palm heart and fruits, in which there was a negative quadratic behavior (Figure 1). This increase in Mn accumulation may be related to the fact that this micronutrient has undergone an internal relocation process and is therefore exported in larger quantities to the leaf organs.

According to Fairhurst & Härdter (2003), the nutritional differences among plant age groups can be explained by the widely nutrient allocation for leaf dry mass production in young oil palm trees, as in the adult plants, nutrients are redistributed to the fruit clusters. Thus, the following decreasing order of Mn accumulation was observed in oil palm plants: leaflets > stipe > petioles > raquis> fruits > male inflorescences > spikelets > central spears > peduncle > palm heart (Figure 1). Of the reproductive organs in the eighth and third year, the fruits presented the highest accumulation of Mn (1601.98 mg plant^{-1}) and the peduncle the smallest (2.97 mg plant^{-1}), respectively (Figure 1f).

The increase in Mn accumulation in plants from two to eight years was probably influenced by the dry mass production of the different organs, as reported in the literature (Viégas *et al.*, 2001). About 45 to 50% of dry mass production is allocated to the growth of male inflorescences and bunches in oil palm producing plants (Corley *et al.*, 1971). Vegetative and reproductive growths are limited, that is, their growth is compromised according to the source used, and competition occurs among different collectors, despite the priority being given to vegetative growth (Corley & Tinker, 2016). A parallel among the Mn accumulations obtained in Malaysia, by Ng *et al.* (1968), and those of the present study, showed a preference for all components in that country, possibly due to the higher dry mass production, combined with the higher content of this nutrient. Regression analysis in these organs showed that the accumulated amount of Mn in the fruit clusters, stipe, tree crown, and male inflorescence, can be estimated by second-degree ascending equations (Figure 2).

Table 2: Variation in Mn concentration in different organs (leaflets, petioles, rachis, palm heart, central spear, stipe, male inflorescences, peduncles, spikelets, and fruits) of oil palm

Organ of plant	Mn concentration (mg kg^{-1})	Variation (%)
Spikelets	130.50 – 223.62	71
Petioles	20.82 – 47.87	130
Rachis	18.25 – 53.62	194
Palm heart	43.25 – 127.25	194
Central spear	31.75 – 57.00	79
Stipes	15.25 – 34.50	126
Males Inflorescences	82.0 – 103.75	26
Peduncle	13.50 – 20.75	54
Spikelets	16.25 – 35.25	117
Fruits	42.75 – 92.25	116

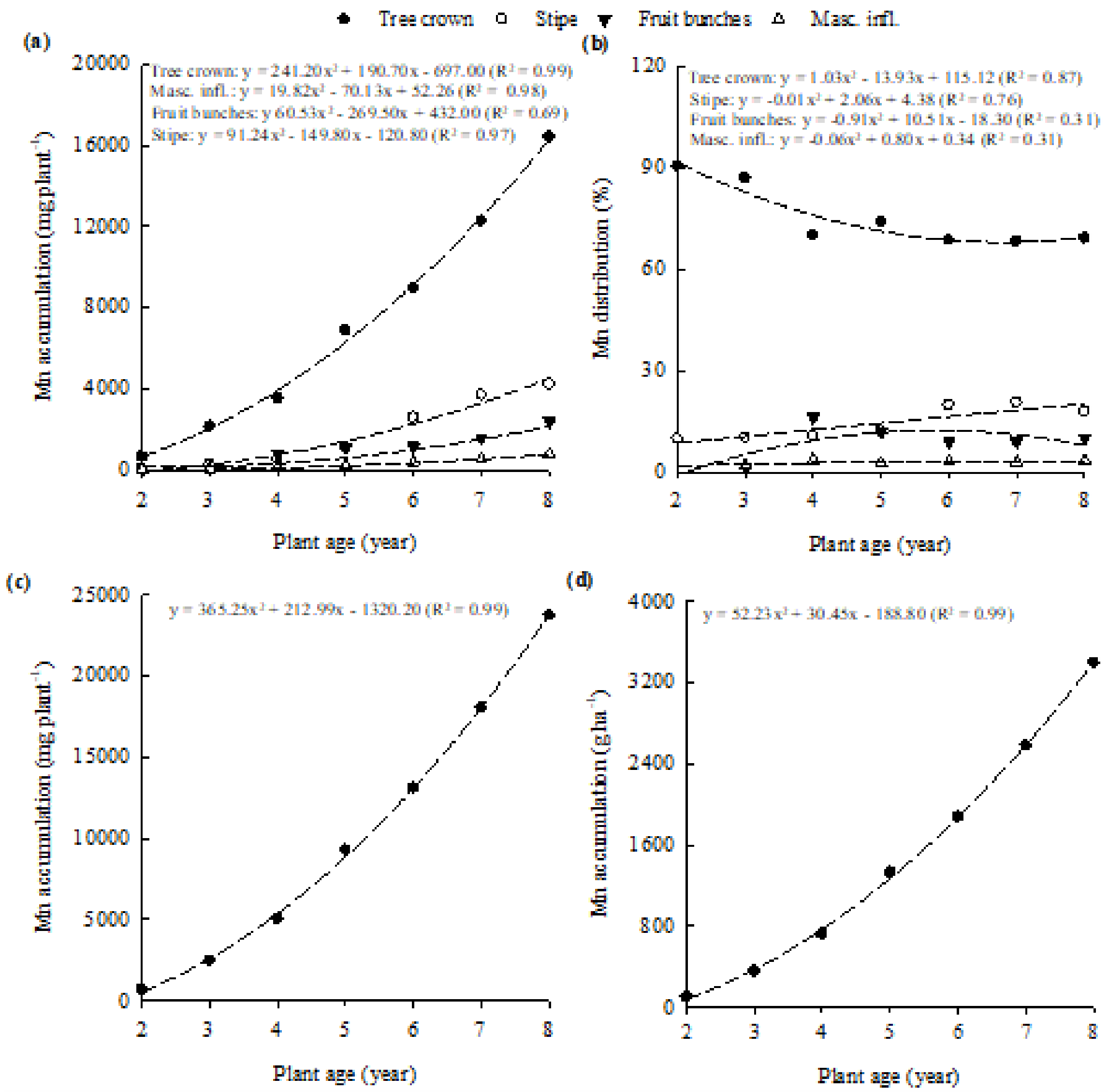

Figure 2: Accumulation (a) and distribution percentage (b) of Mn in the tree crown, stipe, bunches, and male inflorescences and total accumulation of Mn per plant (c) and the total accumulation of Mn per area (d) as a function of the age of oil palm.

The accumulated amount of Mn in the tree crown predominated over that of the stipe, in all years (Figure 2), and the highest allocation of Mn in the tree crown occurred in the leaflets, followed by the petioles, rachis, central spear, and palm heart. The tree crown has an influence on nutrient cycling since the deposition of its organs on the soil between the rows of the plantation provides their return (Viégas *et al.*, 2001). In the present study, in the eighth year, there was accumulation in the tree crown of 16390.11 mg plant^{-1} of Mn, which is equivalent to 2343 g ha^{-1} of the nutrient (143 plants ha^{-1}). According to Chan & Goh (1978), the rachis is known as an organ for storing substantial amounts of nutrients in plants, although it is not commonly used as a reference in oil palm.

The distribution percentage of the accumulated amount of Mn showed clear superiority of the tree crown, in relation to the other organs (Figure 2b). It is also perceived, a slight reduction over the years. The highest total accumulation of Mn was observed in the eighth year and reached 23734.21 mg plant^{-1}, equivalent to 3393.99 g ha^{-1}, with an increasing quadratic response in relation to plant ages (Figures 2c and 2d). Fe and Mn are present in large quantities in weathered tropical soils in the form of oxides and hydroxides (Abreu *et al.*, 2007).

The percentage increase in the total extraction of Mn in the function of the oil palm age increased according to plant development (Figure 3a). In the third year, there was the lowest percentage increase (347.8%) in the total Mn accumulation and the maximum (3338.8%) in the eighth year. The Mn accumulation in the bunches was lower than that of the tree crown and stipe, however, from the fourth year on, it was higher than that of the male inflorescences up to 4.7 times. Due to this fact, good nutrition at a young age is essential for early entry into the harvest and to reach the desired production (Rodrigues, 1993). Thus, the importance of adequate nutrition is emphasized, preventing this nutrient from becoming limiting to crop production. The low availability of nutrients is a limiting factor to plant growth (Fita *et al.*, 2011). Despite the importance of Mn for plants, and the finding of its deficiency in palm oil croplands (Matos *et al.*, 2016), there is still no recommendation of its application for culture under the conditions of Pará (Franzini *et al.*, 2020).

The export of Mn was higher in the bunches (2373.3 mg plant^{-1}) in the eighth year and lower in peduncles (2.97 mg plant^{-1}) in the third year, corresponding, respectively, to 339.38 g ha^{-1} and 0.42 g ha^{-1} (Figures 3b and 3c). The Mn export, except for the fruits, responded in a quadratic way to the age of the plants, however the maximum points were estimated above 8 years of age (Figure 3). The participation of the fruits in the export of Mn ranged from 61.6 to 95.0%, from 3.8 to 34.5% in the spikelets, and from 1.2 to 9.3% in the peduncles, with a lower contribution (Figure 3d). The regression equation that best fit, for the amount exported of Mn by the bunches in the function of plant age, was quadratic $y = 11.32x^2 + 277.9x - 730.6$, $R^2 = 92.3$) (Figure 3b). According to Matos *et al.* (2016), the nutrient export rate, which is considered high in oil palm, is due to the high productivity of these plants.

There are several ways in which the nutrient "status" of a soil cultivated with oil palm can be reduced, such as leaching losses, unavailable nutrients, nutrients used in vegetative development, and export by the fruits. Of these, the export by the fruits contributes substantially, because considerable amounts of nutrients can be removed at the time of the bunches harvest (Viégas, 1993). The amounts of Mn increased with plant development and reached the maximum value of the extracted quantity (3400g ha^{-1}), immobilized (638g ha^{-1}), recycled (2422g ha^{-1}), and exported (339g ha^{-1}) in the eighth year of age (Figure 3e).

The recycled amount of Mn exceeded the immobilization in all plant ages (Fig. 3e). The amount of immobilized Mn was 1.8 times higher than that exported, while the recycled amount was up to 7.0 times higher than that exported. This result is probably because Mn has a characteristic behavior of nutrient that presents medium mobility, in which its content becomes high in the leaf as they become older. Thus, the amount that is recycled from this micronutrient exceeds the immobilized and removed possibly due to its low redistribution in the tissues of plants. Mendes *et al.* (2012) also observed that the Mn content is lower in new rubber tree (*Hevea brasiliensis*) leaves. The oil palm cultivated in the eastern part of the Amazon presents higher concentrations of Mn in the leaflets and male inflorescences, higher accumulated amount in the leaflets and stipe, with increasing age of plants, being more predominant in the tree crown than in the stipe.

The Mn use efficiency increased in all organs as a function of the age of the oil palm plants, obtaining a maximum increase at the eighth time of plant cultivation (Figure 4). The highest Mn use efficiency rates among plant organs were observed in the stipe (2.22 kg² mg^{-1}) and petiole (1.01 kg² mg^{-1}), followed by rachis (0.61 kg² mg^{-1}), spikelet (0.36 kg² mg^{-1}), fruits (0.26 kg² mg^{-1}), peduncles (0.16 kg² mg^{-1}), leaflets (0.14 kg² mg^{-1}), arrows (0.04 kg² mg^{-1}), male inflorescence (0.03 kg² mg^{-1}) and cabbage (0.004 kg² mg^{-1}), considering the average of all crop years.

The results of the study indicate that the Mn use efficiency is modified by the age of the plants (Figure 4), revealing that oil palm plants use the strategy of reusing nutrients from senescent organs to convert them into biomass gains (Siddiqi & Glass, 1981; Prado, 2021) as a function of time and, consequently, increase the Mn accumulation in the different organs of the oil palm (Figure 1). In this scenario, the increase in the Mn use efficiency use in oil palm plants changes the Mn accumulation, consequently, changes the cycling, immobilization, and exportation of Mn as a function of plant age (Figure 3e). Our results reveal that oil palm plants use the strategy of increasing the Mn use efficiency as a function of the age of cultivation to increase the dry mass biosynthesis, modifying the dynamics of immobilization, cycling and exportation of Mn, consequently altering the demand nutritional. Finally, our finding indicates that oil palm plants are efficient in using Mn, increasing the nutrient use efficiency as a function of plant age.

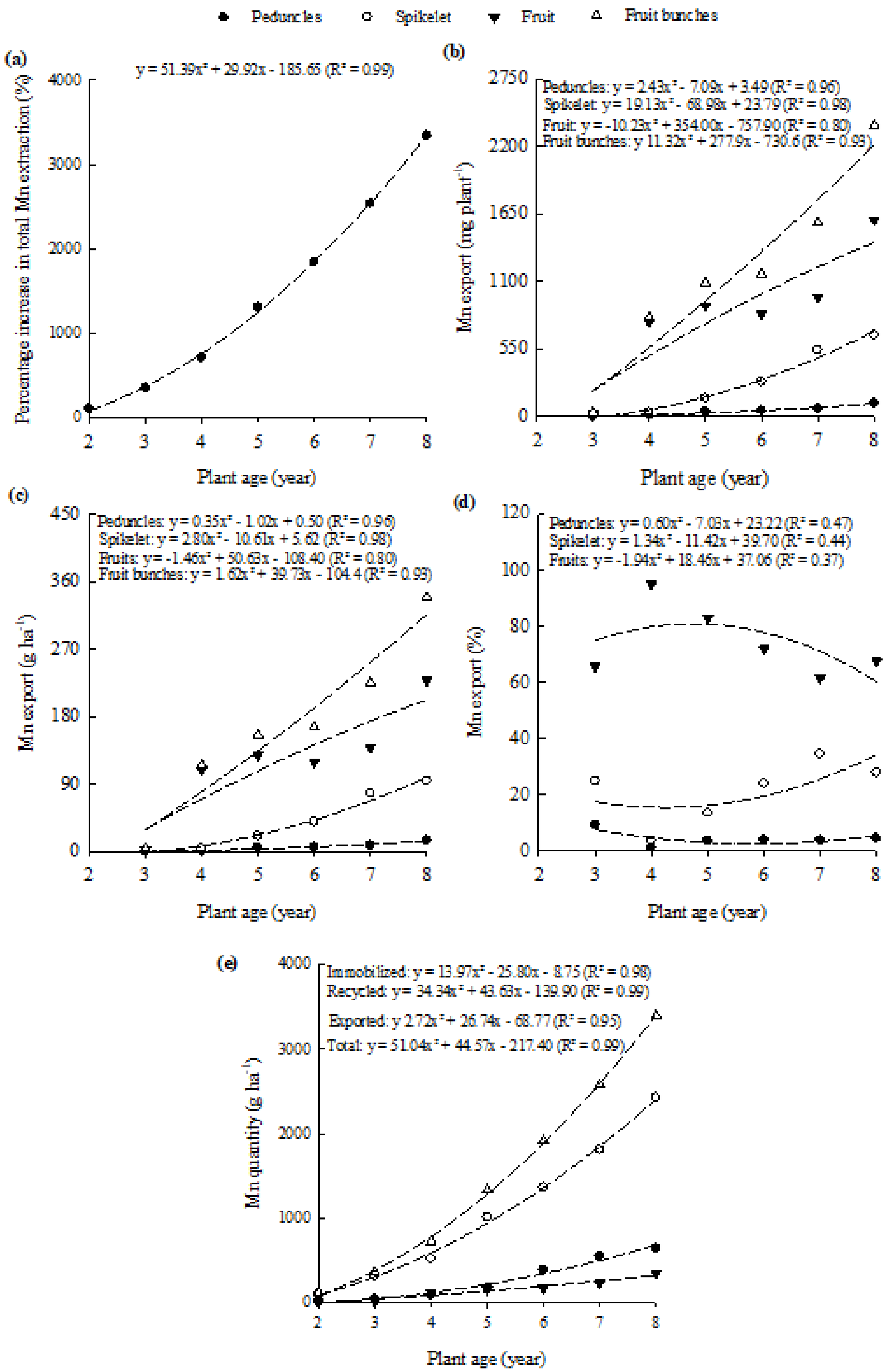

Figure 3: Percentage increase in the total extraction of Mn (a), export (b; c) and percentage distribution (d) of Mn in peduncles, spikelets, fruits, and bunches and amounts of Mn immobilized, recycled, exported and total (e) in the function of oil palm age.

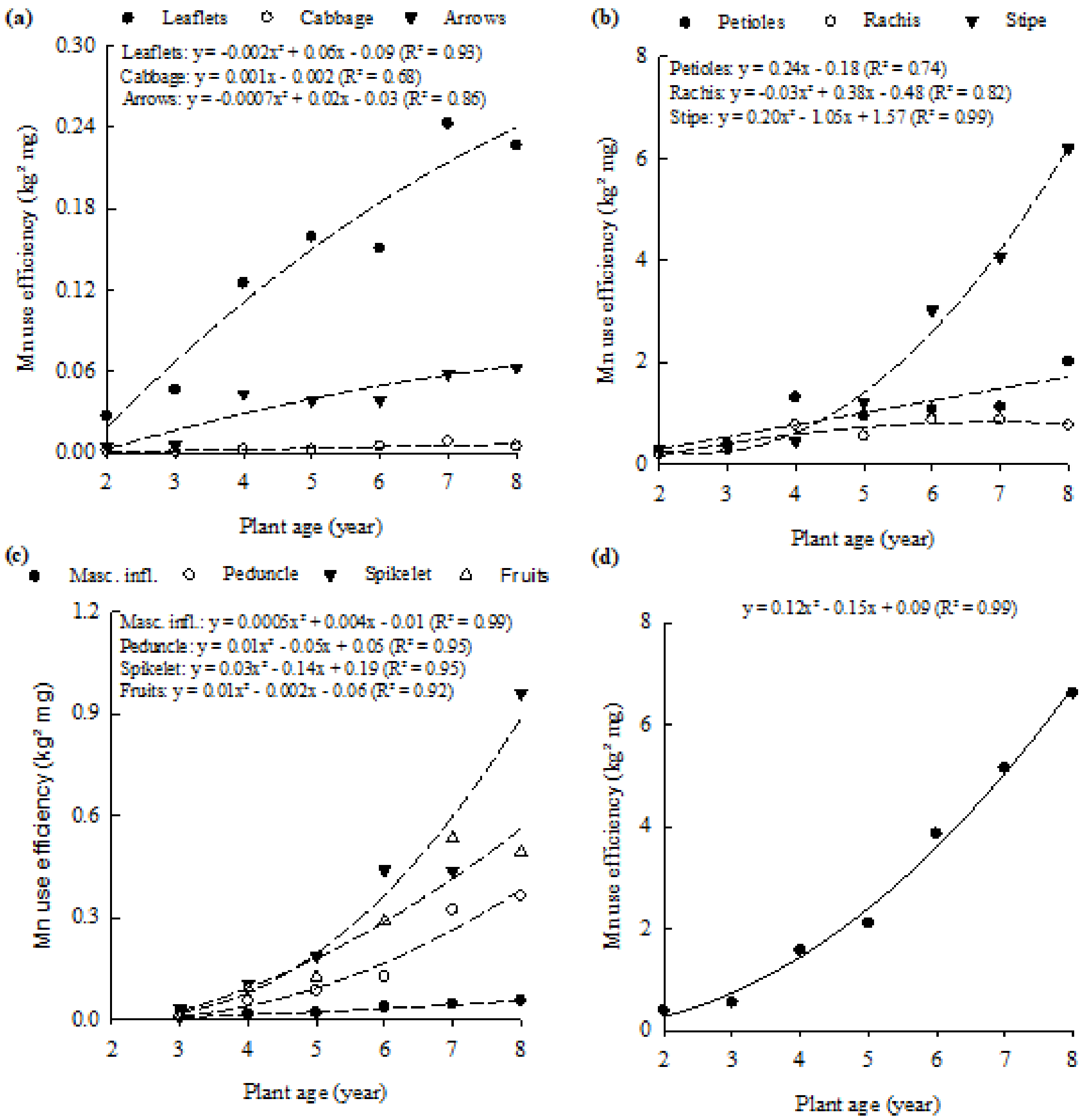

Figure 4: Mn use efficiency in the leaflets, cabbage, arrows (a), petioles, rachis, stipe (b), male inflorescence, peduncle, fruit, and spikelet (c) and total (d) in the function of the oil palm age.

CONCLUSIONS

The oil palm cultivated in the eastern part of the Amazon presents higher concentrations of Mn in the leaflets and male inflorescences, higher accumulated amount in the leaflets and stipe, with increasing age of plants, being more predominant in the tree crown than in the stipe. The amount of recycled Mn is higher than that exported exceeding the immobilized in all plant ages. The highest amounts of exported Mn occurred in oil palm fruits and the smallest occurred in the peduncles, and this export of the nutrient increased with the age of the plants. Oil palm plants are efficient in using Mn, increasing the nutrient use efficiency as a function of age, showing greater use efficiency in the stipe, and decreasing in the petiole, rachis, spikelet, fruits, peduncles, leaflets, arrows, male inflorescence and cabbage.

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CONFLICT OF INTERESTS

There are no conflicts of interest.

REFERENCES

Abreu CA, Lopes AS & Santos G (2007) Micronutrientes. In: Novais RF, Alvarez VVH, Barros NF, Fontes RLF, Cantarutti RB & Neves JCL (Eds.) Fertilidade do solo. Viçosa, Sociedade Brasileira de Ciência do Solo. p.645-736.

Chagas KPT, Carvalho BLB, Guerra CAG, Silva RAR & Vieira FA (2019) Fenologia do dendezeiro e correlações com variáveis climáticas. Ciência Florestal, 29:1701-1711.

Chan KW & Goh KH (1978) Interpretação de dados de folha para dendê. In: Mokhtaruddin & Aminuddin H (Eds.) Métodos Analíticos de Solo e folha, sua técnica. Kuala Lumpur, Sociedade Malaia de Ciência do Solo. p.78-95.

Corley RHV & Tinker PB (2016) The Oil Palm. New York, John Wiley & Sons. 39p.

Corley RHV, Hardon JJ & Tan GY (1971) Analysis of growth of the oil palm (*Elaeis guineensis* Jacq.) I. Estimation of growth parameters and application in breeding. Euphytica, 20:307-315.

Costa SC, Erasmo EAL, Dotto MC & Tavares TCO (2017) Desenvolvimento de híbridos de dendezeiro em condições de Cerrado. Tecnologia & Ciência Agropecuária, 11:25-31.

Cruz Filho D, Viégas IJM, Galvão JR, Silva DR, Pacheco MJB, Souza FJL, Almeida GV & Barata Júnior VP (2019) Biometria e produção de palma de óleo no município de Castanhal (PA). Revista Ibero-Americana de Ciências Ambientais, 10:83-96.

Dufourt F & Quencez P (1979) Étude de la nutrition en oligo-éléments du palmier à huile et du cocotier cultives sur solutions nutritives. Oléagineux, 34:323-328.

Fairhurst T & Härdter R (2003) Oil palm - Management for large and sustainable yields. Singapore, Potash & Phosphate Institute. 382p.

Fernandes RA, Fonseca MR & Martins ASB (2013) Produtividade de feijão caupi em função da calagem e fósforo. Revista Caatinga, 26:54-62.

Ferrand M, Bachy A & Ollagnier M (1951) Les oligoelements dans la fumure du palmier a huile au Moyen-Congo: leur influence sur la santé des arbres. Olégianeux, 6:629-636.

Ferreira DF (2011) Sisvar: a computer statistical analysis system. Ciência e agrotecnologia, 35:1039-1042.

Fita A, Nuez F & Picó B (2011) Diversidade na arquitetura radicular e resposta à deficiência de P em mudas de L. Cucumis melo Euphytica, 181:323-339.

Franzini VI, Matos GSB, Machado DN, Assunção EA, Viégas IJM & Botelho SM (2020) Palma de óleo (Dendezeiro). In: Brasil EC, Cravo MS & Viégas IJM (Eds.) Recomendações de adubação e calagem para o estado do Pará. Brasília, Embrapa. p.281-284.

Gama JRNF, Valente MA, Oliveira Junior C, Cravo MS, Carvalho EJM & Rodrigues TE (2020) Solos do estado do Pará. In: Brasil EC, Cravo MS & Viegas EJM (Eds.) Recomendações de adubações e calagem para o estado do Pará. Brasília, Embrapa. p.25-46.

Homma AKO & Rebello FK (2020) Aspectos econômicos da adubação e da calagem na Amazônia. In: Brasil EC, Cravo MS & Viégas IJM (Eds.) Recomendações de adubação e calagem para o estado do Pará. Brasília, Embrapa. p.185-204.

Jacquemard JC (1979) Contribution à l'étude de la croissance en hauteur du stipe d'Elaeis guineensis Jacq. Étude du croisement LT x 010D. Oléagineux, 34:492-495.

Lebid T & Henkes JA (2015) Óleo de dendê na produção de biodiesel: um estudo de caso das vantagens e desvantagens econômica, ecológica e social da cultura desta oleaginosa para a produção de biodiesel. Revista gestão e sustentabilidade ambiental, 4:416-447.

Lopes AS & Guilherme LRG (2007) Fertilidade do solo e produtividade agrícola. In: Novaes RF, Alvarez VH, Barros NF & Neves JCL (Eds.) Fertilidade do solo. Viçosa, Sociedade Brasileira de Ciência do Solo. p.01-64.

Malavolta E, Vitti GC & Oliveira SA (1997) Avaliação do estado nutricional das plantas: princípios e aplicações. Piracicaba, Potafos. 319p.

Matos GSB, Fernandes AR & Wadt PGS (2016) Níveis críticos e faixas de suficiência de nutrientes derivados de métodos de avaliação do estado nutricional da palma-de-óleo. Pesquisa Agropecuária Brasileira, 51:1557-1567.

Mendes ADR, Oliveira LEM, Nascimento MN do, Reis KL & Bonome LTS (2012) Concentração e redistribuição de nutrientes minerais nos diferentes estádios foliares de seringueira. Acta Amazônica, 42:525-532.

Nabun JS, Santos CB & Carvalho ACA (2017) Dinâmicas da agricultura familiar com cultura do dendezeiro no município de Moju, na Amazônia paraense. Revista Novos Cadernos NAEA, 20:161-180.

Nachtigall GR, Nogueirol RC & Alleoni LRF (2009) Extração seqüencial de Mn e Zn em solos em função do pH e adição de cama-de-frango. Revista Brasileira de Engenharia Agrícola e Ambiental, 13:240-249.

Ng SK & Thamboo S (1967) Nutrient contents of oil palms in Malaya. I. Nutrients required for reproduction: fruit bunches and male inflorescence. The Malaysian Agricultural Journal, 46:03-45.

Ng SK, Eng TC & Thamboq S (1968) Nutrient contente of oi1 palm in Malaya. III. Micronutrients contents in vegetative tissues. The Malaysian Agriculture Journal, 46:412-433.

Pirker J, Mosnier A, Kraxner F, Havlik P & Obersteiner M (2016) What are the limits to oil palm expansion? Global Environmental Change, 40:73-81.

Prado RM (2021) Mineral nutrition of tropical plants. New York City, Springer Publishing. 339p.

Rodrigues MRL (1993) Resposta do dendezeiro (*Elais guineenses* Jacq.) à aplicação de fertilizantes nas condições do médio Amazonas. Master Dissertation. Universidade de São Paulo, Piracicaba. 91p.

Rodrigues MRL, Amblard P, Silva EB, Macêdo JLV, Cunha RNV & Tavares AM (2002) Avaliação do estado nutricional do dendezeiro: análise foliar. Manaus, Embrapa. 10p.

Rodrigues TE, Silva JML, Silva BNR, Valente MA, Gama JRNF, Santos ES, Rollim PAM & Ponte FC (2005) Caracterização e classificação dos solos do município de Tailândia, estado do Pará. Belém, Embrapa Amazônia Oriental. 55p.

Rognon F (1984) Analyse vegetable dans controle de I'alimentation des plantes. Paris, Palmier à Huile. 446p.

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo filho JC, Oliveira JB & Cunha TJF (2018) Sistema Brasileiro de Classificação de Solos. 5ª ed. Brasília, Embrapa. 356p.

Siddiqi MY & Glass ADM (1981) Utilization index: A modified approach to the estimation and comparison of nutrient utilization efficiency in plants. Journal of Plant Nutrition, 4:289-302.

Silva IR & Mendonça ES (2007) Matéria orgânica do solo. In: Novais RF, Alvarez VVH, Barros NF, Fontes RLF, Cantarutti RB, Neves JCL (Eds.) Fertilidade do solo. Viçosa, Sociedade Brasileira de Ciência do Solo. 275-374p.

Singh R (1984) Disponibilidade de micronutrientes em classes dominantes de solos do trópico úmido brasileiro. Belém, Embrapa. 17p.

Surre E (1979) Croissance en hauteur du palmier à huile. Oléagineux, 34:491-491

Viégas IJM (1993) Crescimento do dendezeiro (*Elaeis guineenses* Jacq.), concentração, conteúdo e exportação de nutrientes nas diferentes partes de plantas de dendezeiro com 2 a 8 anos de idade, cultivadas em Latossolo Amarelo distrófico, Tailândia, Pará. Doctoral Thesis. Universidade de São Paulo, Piracicaba. 217p.

Viégas IJM, Conceição HEO, Botelho SM, Frazão DAC, Pimentel MJO & Thomaz MAA (2001) Crescimento e produção de matéria seca em diferentes partes de dendezeiro dos 2 aos 8 anos de idade. Revista Ciências Agrárias, 36:67-81.

Viégas IJM, Galvão JR, Silva AO, Conceição HEO, Pacheco MJB, Viana TC, Ferreira EVO, Okumura RS & Silva DAS (2020) Chlorine nutrition of oil palm tree (*Elaeis guineenses* Jacq) in Eastern Amazon. Journal of Agricultural Studies, 8:704-720.

Viégas IJM, Pimentel MJO, Galvão JR, Silva DAS, Ferreira EVO, Silva Júnior ML, Yakuwa TKM & Lima SKS (2019) Adubação mineral na fase produtiva da palma óleo (*Elaeis guineenses* jacq) cultivada na região Amazônica. Revista Ibero-Americana de Ciências Ambientais, 10:274-286.

Viégas IJM, Costa MG, Ferreira EVO, Lima EV, Silva Junior ML & Silva DAS (2021) Micronutrients concentrations in leaves of oil palm trees fertilized with phosphorus, potassium, and magnesium. Journal of Agricultural Studies, 9:377-393.

Vitti GC, Oliveira DB & Quintino TA (2006) Micronutrientes na cultura da cana-de-açúcar. In: Segato SV, Pinto AS, Jendiroba E & Nóbrega JCM (Eds.) Atualização em produção de cana-de-açúcar. Piracicaba, Livroceres. p.121-138.

Wilkinson RE & Ohki K (1988) Influence of manganese deficiency and toxicity on isoprenoid syntheses. Plant Physiology, 87:841-846.

Woittiez LS, Wijk MV, Slingerland M, Noordwijk MV & Giller KE (2017) Yield gaps in oil palm: A quantitative review of contributing factors. European Journal of Agronomy, 83:57-77.

Zakaria ZZ & Gammon NJR (1979) The copper, zinc, manganese, iron, and aluminum contents of soils commonly used for *Hevea brasiliensis* cultivation. Distribution within soil profiles. Journal of the Rubber Research Institute of Malaysia, 27:68-78.