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Full Length Article

Cultivation Age of Oil Palm Plants Alters the Dynamics of Immobilization, Recycling and Export of Sulfur and Increases its use Efficiency

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Abstract

This study aimed to evaluate sulfur (S) nutrition in oil palm organs as a function of plant age. The experiment was carried out in the commercial plantations of the company Agropalma S/A (Municipality of Tailândia, Pará State, Brazil) in a dystrophic Yellow Latosol. The experiment design was completely randomized with four replications and seven treatments: plant ages (2, 3, 4, 5, 6, 7 and 8 years). The effects of treatments were evaluated in terms of concentration, accumulation, immobilization, recycling, export, and use efficiency of S in each plant organ. In the 8th year, the highest S concentration in the vegetative organs occurred in the cabbage (palm heart), while male inflorescence had higher S concentration in the 7th year in the reproductive organs. As plant age advanced, stipe and fruits were, respectively, the vegetative and reproductive organs that presented higher S accumulation. In older plants, S export occurs at higher amounts in the bunches. In oil palm, the immobilized and recycled quantity of S is higher than that exported. The use efficiency increased in the different organs of oil palm proportionally to the increase in plant age, while the S use efficiency in the rachis was 2630 times greater than that in the cabbage. In conclusion, oil palm plants change the nutritional demand as a function of age, increasing the S use efficiency and modifying the dynamics of immobilization, recycling, and export of S.

Keywords: Accumulation; Concentration; Export; Efficiency; S Recycled; S immobilized

Introduction

Oil palm (*Elaeis guineensis* Jacq.) is intensively cultivated in the tropics, with a production cycle of 25–30 years, an average yield of 4 tons of oil ha^{-1} year^{-1} and high capacity to perform carbon sequestration (Queiroz *et al.* 2012; Costa *et al.* 2018). Oil palm is considered the most important oilseed culture worldwide (Sheil *et al.* 2009). Oil palm is a perennial crop and its cultivation has been widely used as an alternative for regional socioeconomic development as well as in the recovery of degraded areas in the Amazon region (Costa *et al.* 2018). The largest oil palm crops are in the Amazon region and eastern Amazon alone concentrates roughly 80% of the country's plantation (Chia *et al.* 2009; Nahun *et al.* 2020).

In the Amazon region, there is predominance of Latosols and clayey soils, which are soils with physical properties suitable for agricultural use, but highly weathered and with low nutrient availability (Gama *et al.* 2020). According to Silva *et al.* (2006), cultivation in these soils requires determining the nutritional requirements and deficiencies of crops. The capacity of soils to meet plant nutritional needs is closely related to the organic matter (OM) content and its mineralization, which gradually makes sulfur (S) available to the soil solution in the form of sulfate to be absorbed by the plant (Vitti *et al.* 2018). However, little is known about the nutritional requirement of S for the oil palm crop. It is not known the S accumulation rates and in which organs the greatest accumulation occurs, consequently, it is not understood the interaction of S with crop performance.

According to Moline and Coutinho (2015), there is little change in the levels of available S in areas with primary forest cover with good drainage, preserved surface horizon and rich in OM, increasing with soil depth. Sulfur in the soil is found mainly in the organic form; however, its immediate availability can be controlled by the adsorption and desorption processes of sulfate through the rapid balance between the solution sulfate and the soil solid phase. Sulfate adsorption depends mainly on the content and type of clay

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minerals and oxides in the soil. The functional groups of the broken edges of kaolinite and iron oxide surface have the highest retention capacity of this ion (Peak *et al.* 1999).

Sulfur deficiency is rather common in several tropical regions (Horowitz and Meurer 2006). In the Amazon region, the OM content deposited in the surface layers tends to reduce with the decrease of native forest areas thus decreasing S availability to plants (Moline and Coutinho 2015). Sulfur is essential to plant nutrition and its main function is related to nitrogen (N) metabolism (Paiva and Nicodemo 1993). According to Sabir *et al.* (2015), S is of paramount importance for oil palm, as it is related to the formation of organs of saturated fatty acid storage and oil biosynthesis. For the conditions of Amazon, S is reported as one of the nutrients with the highest incidence of deficiency in oil palm crops (Matos *et al.* 2019). Therefore, fertilizer use is essential to ensure high crop yields, with recommendations of 20 kg ha^{-1} of S to reach an average yield of 17 t ha^{-1} of fresh fruits.

Sulfur dynamics in oil palm plants are not entirely understood and the lack of knowledge on the rates of immobilization, export and recycling of S in crops in the Amazon region restricts the tools for crop nutritional management. To advance the understanding of S nutrition at different ages of oil palm crops, the hypotheses are tested: (i) S nutritional requirement increases with crop age due to increased biomass accumulation and increased nutrient exports by fruits and (ii) S accumulation in the different oil plant organs occurs in different ways, since S acts in specific activities in photosynthesis and enzymatic activities in specific sites of reactions in certain plant organs.

The understanding of S requirements at different oil palm ages allows for a better nutritional management and yield gains, ensuring sustainable management in the Amazon region. This study aimed to evaluate the dynamics of concentration, accumulation, and efficiency of use of S and their impacts on the immobilization, recycling, and export of S at different ages of oil palm crops in Eastern Amazon.

Materials and Methods

Experimental conditions

The experiment was carried out in commercial oil palm crops at the company Agropalma in the municipality of Tailândia (2° 56' 50" S and 48° 57' 11" W), Pará State, Brazil. The region has Ami type (rainy tropical) (Köppen climate classification). The region has annual averages of 26ºC of temperature and 2,300 mm of precipitation with a less rainy period between July and December (Matos *et al.* 2016). During the experimental period, rainfall was evaluated by a rain gauge installed on site with an average of 2,409 mm $year^{-1}$.

The soil in the experimental site is classified as dystrophic Yellow Latosol (Rodrigues *et al.* 2005), characterized as acidic, deep, well drained, usually with medium texture and high density (Santos *et al.* 2018). The soil composite samples were collected in the surface layer (0–30 cm) of the planting rows, taken from four subsamples, for each age of the oil palm crop. Subsequently, the soil physical analyses (Table 1) were performed at the Center for Agroforestry Research of Eastern Amazonia-CPATU/EMBRAPA. For the analysis of soil chemical attributes (Table 1), the samples were sent to the Laboratory of the Department of Soil Science of the College of Agriculture Luiz de Queiroz (ESALQ/USP).

Experimental design

A split plot design was used with four replications and seven treatments: different plant ages (2, 3, 4, 5, 6, 7 and 8 years of planting) and each plant represented an experimental unit. The experimental plots were composed by healthy plants, selected from the common features of the plant population. The following criteria were determined to select homogeneous plants: plants preferably in the same portion, representative of age, well developed, nourished, uniform, with high yield and without attacks of insects and pathogens. Stem circumference and plant height were measured to select the mean of the plot and reduce heterogeneity, starting from the base of leaf 33, which corresponds to the height of the mature bunch to be harvested.

Management conditions and installations of experimental plots

We used the commercial hybrid Tenera (Dura x Psifer), cultivated in an equilateral triangle in a spacing of 9 x 9 m and totaling 143 plants/ha. In all plots, the soil was covered with the legume *Pueraria phaseoloides* L. Table 2 shows information on crop yield and fertilization applied according to plant age. The sources of N, P, K, and Mg used were, respectively, urea (45% N), reactive natural phosphate (33% P_2O_5 and 42% CaO), potassium chloride (60% K_2O and 45% Cl) and magnesium sulfate (18% MgO and 13% S).

Experimental evaluations

Dry matter determination: After selection, the complete plants at the base of the stipe were collected. Subsequently, the plant material was separated into petioles, rachis, leaflets, cabbage, stipe, peduncles, arrows, male inflorescence, spikelets, and fruits. The collections were carried out concomitantly in all plantations of the study to determine the fresh matter of each component (FMEC).

The collected plant material was sent to the laboratory in which a subsample (SS) was removed, stored in a paper bag, and dried in an oven of forced air circulation (70°C) until it reached constant mass. Then, dry matter (DM) of subsamples (DMSS) of the different vegetative organs was quantified. The product quotient of the subsample dry mass, the fresh mass of each component, and the fresh mass of the subsample were calculated to obtain DM of each plant part (Equation 1).

$$DM\ (g) = \frac{DMSS * FMEC}{SS} \qquad (Equation\ 1)$$

Determining S concentration: The plant tissue was ground in a Willey Mill and then the plant material was digested using the nitric-perchloric method. Sulfur concentration in each organ was determined using the turbidity method with the aid of atomic absorption spectrophotometry (Malavolta *et al*. 1997). The variation of S concentration in oil palm crops was calculated for each component, defining the upper value of the variation range by the sum of the arithmetic mean and the standard deviation. The lower value of the variation range was defined by the mean difference arithmetic and standard deviation. The variation in concentrations was estimated from the standard deviation quotient and the arithmetic mean and subsequently multiplied by 100.

Determining S accumulation: Sulfur accumulation was calculated from the product of dry mass and S concentration for the different organs evaluated (Equation 2). Sulfur accumulation in the plant crown and bunches was estimated by the sum of S accumulation in the leaflets, petioles and rachis for the crown and fruits and peduncle and spikelet for the bunches.

$$S\ accumulation\ (g\ per\ plant) = \frac{Dry\ matter\ (g)\ x\ concentration\ (g\ kg^{-1})}{1000} (Equation\ 2)$$

The percentage distribution of S accumulation in the crown and stipe was calculated by estimating the accumulation ratio in the component (crop or stipe) and the sum of both components (crop + stipe). Furthermore, the percentage distribution of S accumulation in the bunches and male inflorescence was estimated by using the ratio of the component studied (bunches or male inflorescence) and the sum of S accumulation in the bunches and male inflorescence. Finally, the total accumulation of S per planting area (ha) was estimated by considering the product of S accumulation per plant and the number of plants per hectare (143 plants).

Determining immobilization, recycling, and export rates of S: Sulfur immobilization rates were calculated from the sum of S accumulation in the cabbage, stipes and arrows. Recycling rates were obtained from S accumulation in leaflets, petioles, male inflorescences, and rachis. For the rates of S exports, S accumulation in the bunches was considered and estimated from the sum of S accumulations in the fruits, peduncles, and spikelets. Additionally, the relative values of S exports for fruits, peduncles and spikelets were calculated using the component ratio (fruits or peduncles or spikelets) and the sum of exported components (fruits + peduncles + spikelets). Finally, the export of S per area (ha) was calculated, considering the product of the quantity of S exported per component and the number of plants per area in hectares (143 plants).

Determining S use efficiency: Sulfur use efficiency in the different organs and the total plant was estimated from the ratio between the dry mass square and S accumulation (Siddiqi and Glass 1981).

Data analysis

Preposition tests were performed, calculating Levene's homogeneity and Shapiro-Wilk normality. The variance analysis (F test; $p<0.05$) and adjustments of regression models were performed using the results of the S analyses in plant organs at different oil palm ages, using the statistical software Sisvar (Ferreira 2011).

Results

Sulfur concentrations were influenced by plant age in the different organs of the oil palms, except for rachis and leaflets (Fig. 1). In vegetative organs, the highest S concentration was in palm heart (5.6 g kg^{-1}) in the 8th year, while rachis presented lower accumulation (0.1 g kg$^{-1)}$, remaining constant in all years (Fig. 1b and c). There was a negative quadratic response in S concentration in the vegetative organs petiole and stipe as a function of plant age (Fig. 1a and c). On the other hand, S concentration in palm heart and arrows responded to the positive quadratic model to plant age (Fig. 1b and c). The maximum S concentration in the vegetative organs petiole (0.68 g kg^{-1}) and stipe (1.77 g kg^{-1}) was estimated at 5.4 years of plant age (Fig. 1a, c).

Among the reproductive organs, male inflorescence presented the highest S concentration (3.1 g kg^{-1}) in the 7th year, while the lowest concentration (0.1 g kg^{-1}) occurred in the spikelets during the 3rd year of planting (Fig. 1d–e). Sulfur concentration in male inflorescence and fruits showed an increasing quadratic response until the 6th year (Fig. 1d, f). Maximum S concentration in the reproductive organs male inflorescence and fruits were estimated at 6.6 and 5.5 years of plant age, with averages of 3.01 and 1.50 g kg^{-1}, respectively (Fig. 1d, f). Peduncles and spikelets had an increase in S concentration due to the increase in plant age (Fig. 1e). Sulfur concentrations in vegetative and reproductive organs showed a variation according to oil palm ages under study, mainly in petiole (86%) 0.1 to 0.7 g kg^{-1} S (Table 3). On the other hand, rachis did not present variation in its S concentrations (0.1 g kg^{-1}) at the different plant ages.

Sulfur accumulation in the different components of oil palm as a function of plant age showed a linear increase in all cases, with a maximum value obtained in the 8th year (Fig. 2a and b). The highest S accumulation was verified in the stipe (214 g plant^{-1} of S) in the 8th year, equivalent to 58% of the total plant (Fig. 2c). On the other hand, in the 3rd year, the lowest accumulation (0.58 g plant^{-1} of S) occurred in the clusters, representing 1.8% of the total plant (Fig. 2d). In quantitative terms, S accumulation in the 8th year followed the order stipe > crown > bunches > male inflorescence (Fig. 2).

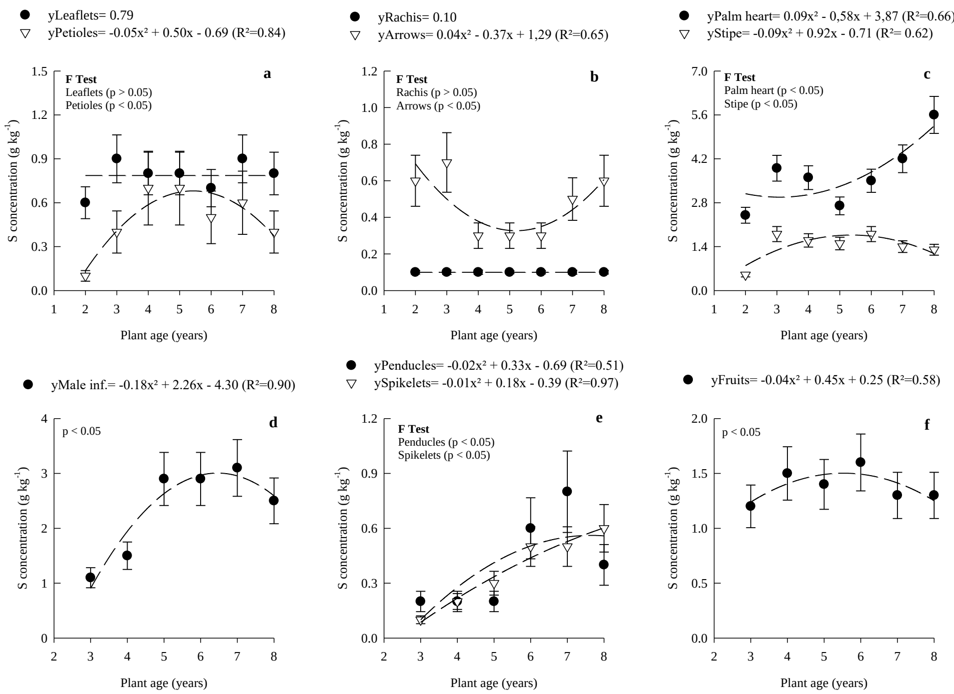

Fig. 1: Sulfur concentration in the leaflets and petioles (a), rachis and arrow (b) and palm heart and stipe (c), male inflorescence (d), peduncles and spikelets (e) and the fruits (f) as a function of oil palm plant age

Table 1: Soil chemical and physical features (0–30 cm) of oil palm plantations with different ages

Feature	Plant age (years)						
	2	3	4	5	6	7	8
pH ($CaCl_2$)	4.3	4.4	4.1	4.0	4.0	4.3	4.0
K* ($cmol_c$ dm^{-3})	0.07	0.06	0.05	0.07	0.05	0.05	0.06
Ca* ($cmol_c$ dm^{-3})	0.7	0.7	0.9	0.8	0.7	0.7	0.6
Mg* ($cmol_c$ dm^{-3})	0.4	0.2	0.2	0.3	0.3	0.3	0.3
Al ($cmol_c$ dm^{-3})	0.4	0.3	0.3	0.5	0.8	0.4	0.6
H+Al** ($cmol_c$ dm^{-3})	3.4	2.8	3.1	3.8	3.4	2.6	3.4
SB ($cmol_c$ dm^{-3})	1.17	0.96	1.15	1.17	1.05	1.05	0.96
P* (mg dm^{-3})	4	6	5	6	6	6	8
V (%)	24	24	26	22	22	27	20
OM*** (g dm^3)	1.6	2.3	1.5	1.9	2	2.1	1.8
Coarse sand (g kg^{-1})	450	320	500	370	380	340	510
Fine sand (g kg^{-1})	280	300	190	310	210	320	230
Tags (g kg^{-1})	40	160	80	100	80	100	60
Clay (g kg^{-1})	230	220	230	220	330	240	200

*Extracted with ion exchange resin. ** SMP method. Colorimetric method

Table 2: Plant age, yield, and mineral fertilization of the oil palm trees evaluated

Plant age	Yield	Mineral fertilization					
(Years)	t ha^{-1}	n	P_2The_5	K_2O	Mg	S	H_3BO_3
		---------------------- g/plant ----------------------					
2	-	35	60	60	-	24	-
3	1.5	18	77**	154	-	-	-
4	7.0	56	115	300	60	45	-
5	9.0	97	336	240	60	45	-
6	15.0	135	470	335	77	58	-
7	19.0	135	470	335	102	58	50
8	20.0	160	384	324	68	52	60

** Application of 500 kg ha^{-1} of phosphine (rock phosphate).

Table 3: Variation in S concentration in different vegetative organs (leaflets, petioles, rachis, palm heart, arrows, and stipes) and reproductive (male inflorescences, peduncles, spikelets and fruits) of oil palm

Plant organ	S concentration (g kg^{-1})	Variation (%)
Leaflets	0.6 – 0.9	50
Petioles	0.1 – 0.7	86
Rachis	0.1 – 0.1	0
Palm heart	2.4 – 5.6	57
Arrows	0.3 – 0.7	57
Stipe	0.5 – 1.8	72
Male Inflorescences	1.1 – 3.1	65
Peduncles	0.2 – 0.8	75
Spikelets	0.1 – 0.6	83
Fruits	1.2 – 1.6	25

Sulfur accumulation had the lowest values in the 2nd year, mainly in arrows and palm heart, 0.13 and 0.19 g $plant^{-1}$, respectively (Fig. 3). For stipe (Fig. 2a), leaflets (Fig. 3a) and peduncles and fruits (Fig. 3c), S accumulation was explained by linear equations, while it was explained by quadratic equations of plant age in petiole, rachis, palm heart, arrows and spikelets (Fig. 3a, b and c). The fruit was the reproductive organ with the highest S accumulation (37 g $plant^{-1}$) in the 8th year, while the peduncle had the lowest S accumulation (0.03 g $plant^{-1}$ of S) in the 3rd year. This relationship between S accumulation and plant age is explained by increasing linear equations for vegetative organs, except for spikelets, which are represented by quadratic equation (Fig. 3). In

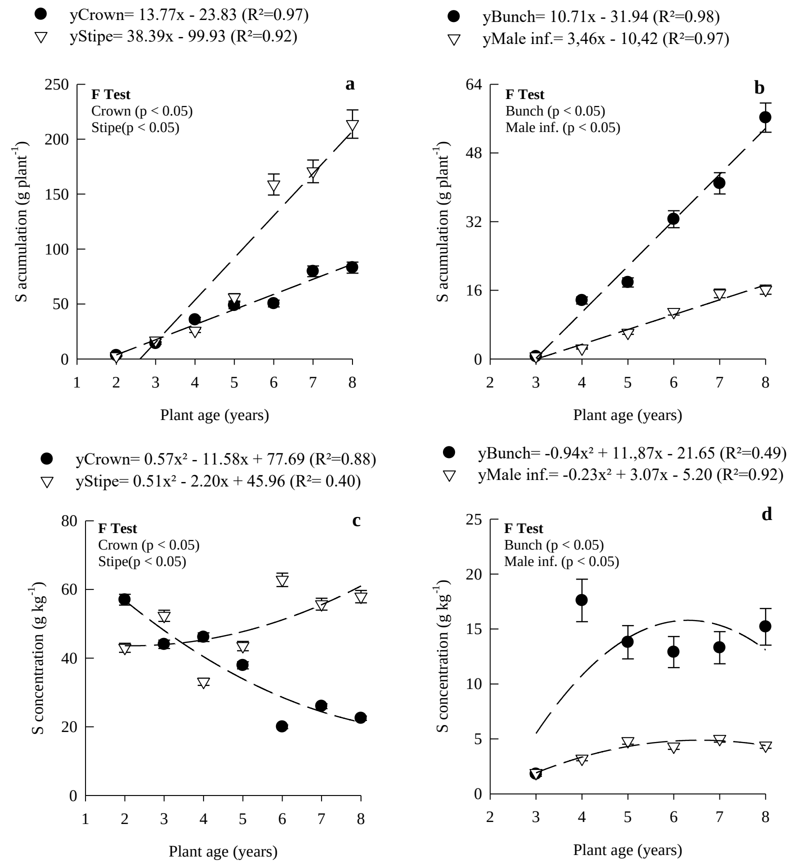

Fig. 2: Sulfur accumulation in the crown and stipe (a), bunches and male inflorescence (b and percentage distribution of S in the crown and stipe (c), male bunches and inflorescences (d) as a function of oil palm plant age

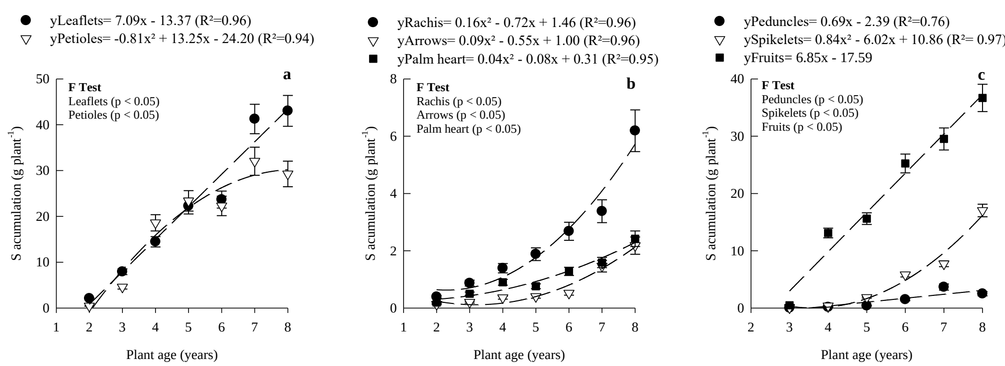

Fig. 3: Sulfur accumulation in leaflets and petioles (a), rachis, palm heart and arrows (b), peduncles, spikelets, and fruits (c) as a function of the age of oil palm plant age

quantitative terms, considering the average of all the years of the plants evaluated, S accumulation followed the order stipe > leaflets > petioles > fruits > male inflorescences > spikelets rachis > peduncles > palm heart > arrows (Fig. 2–3).

Total S accumulation in greater quantity was verified in the 8th year with 53 kg ha^{-1} about 369 g plant^{-1} in an increasing quadratic relationship with plant age (Fig. 4a–b). For S fertilization, 282 g plant^{-1} of S (Table 2) was applied, below the value extracted by the plant in the 8th year (Fig. 4b).

The percentage increase in S extraction also increased with plant age (Fig. 4c). Thus, the lowest increase of total S accumulation (559%) occurred in the 3rd year, while the maximum percentage of accumulation occurred (6438%) in the 8th year.

Sulfur showed the lowest export in the peduncles in the 3rd year and the highest in the bunches in the 8th year, equivalent to 0.03 g plant^{-1} and 56 g plant^{-1}, respectively (Fig. 5a and c). Sulfur exports increased with plant age, according

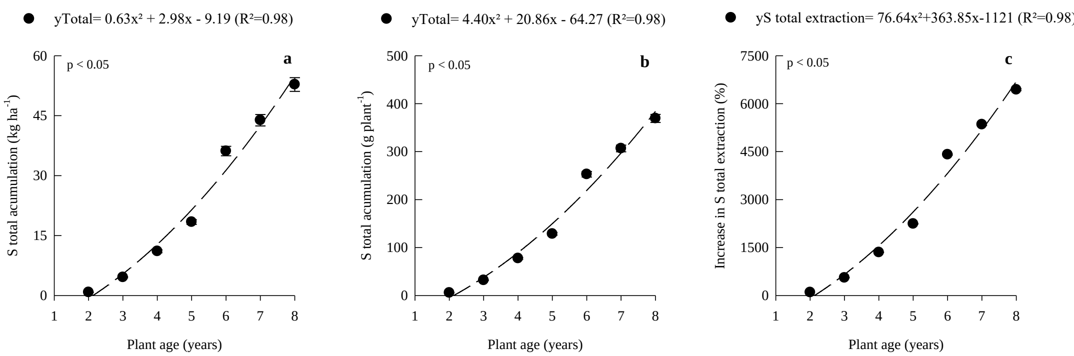

Fig. 4: Total accumulation of S per area (a), total accumulation of S per plant (b), and percentage increase in total extraction of S as a function of oil palm plant age

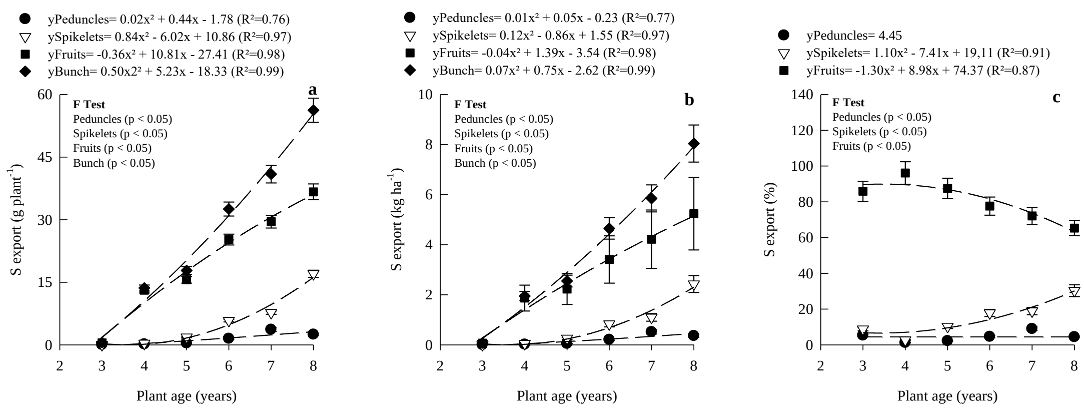

Fig. 5: Sulfur export per plant (a) and area (b) and percentage distribution (c) in peduncles, spikelets, fruits and bunches as a function of oil palm plant age

to the quadratic model (Fig. 5). The percentage variation showed that S export by the peduncle ranged from 1.2 to 5.3%, in the spikelets from 2.7 to 30.3% and from 65.3 to 96.1% in the fruits (Fig. 5c). Sulfur amounts S increased with plant age, reaching the maximum total value (53 kg ha^{-1}), immobilized (31 kg ha^{-1}), recycled (14 kg ha^{-1}) and exported (8 kg ha^{-1}) in the 8th year of planting (Fig. 6).

Sulfur use efficiency increased in all organs with oil palm plant age, with the greatest increase occurring in the 8th year (Fig. 7). The highest S use efficiency was observed in the rachis (184.1 kg^2 g^{-1}), while the lowest efficiency was obtained in the cabbage (0.07 kg^2 g^{-1}), following the decreasing order of rachis > petiole > stipe > leaflet > spikelet > fruits > peduncles > arrows> male inflorescence > palm heart (Fig. 7).

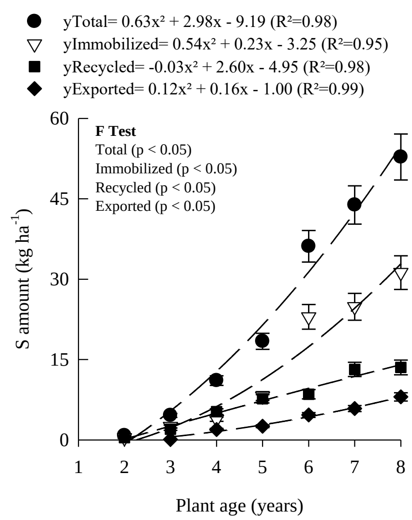

Fig. 6: Amounts of S immobilized, recycled, exported and total as a function of oil palm plant age

Discussion

The current study reveals S dynamics in oil palm plants, showing that changes occur in the rates of recycling, immobilization and export of S (Fig. 6) at different plant ages. These facts contribute to the understanding of changes in S concentration and accumulation in plants, indicating that age is a determining factor to change S dynamics. This understanding contributes to improve crop nutritional management, showing that plant age must be considered to assess the crop nutritional status.

There is a recommendation of 2.5 to 4.0 g kg^{-1} of S for an optimal range of leaf concentration for plants with less

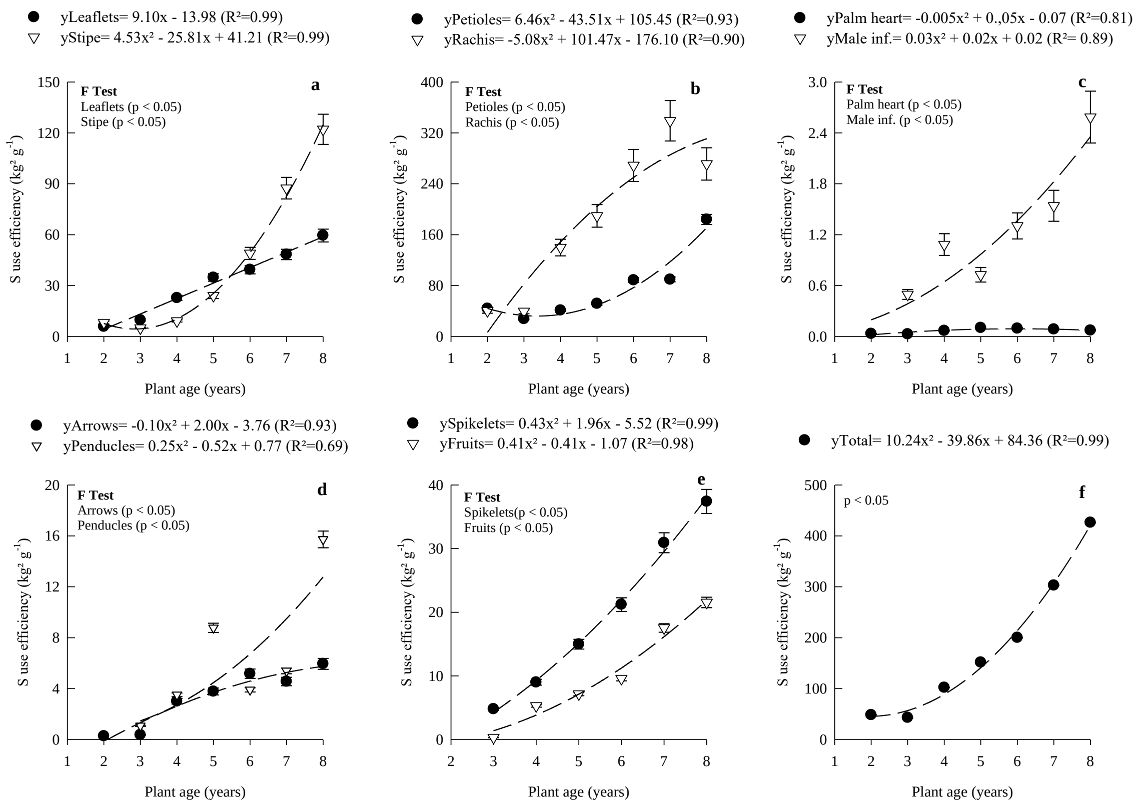

Fig. 7: Sulfur use efficiency in the leaflets and stipe (a), petioles and rachis (b) and palm heart and male inflorescence (c), arrows and peduncles (d), spikelets and fruits (e) and the total (f) as a function of oil palm plant age

than six years of age and 2.5 to 3.5 g kg^{-1} for plants with more than six years (Uexkull and Fairhust 1991). However, our results suggest that the division of only two groups is not sufficient to accurately ensure the crop nutritional status. Our results show that leaf concentrations varied by 50% for a period of 2–8 years, indicating that shorter periods should be considered for the sufficiency ranges, since ranges present greater variations in long periods, consequently, less precision in the evaluation of the plant nutritional status. In addition, different genotypes have different nutritional requirements and the interspecific hybrid O x G [*Elaeis oleiferous* (Kunth) Cortés x *Elaeis Guineis* Jacq] is more demanding than Tenera (Matos *et al*. 2019).

Sulfur concentrations in different plant organs change depending on nutrient accumulation rates, as S accumulation rates reflect the amount of S absorbed by oil palm plants. In general, organs of older plants show greater S accumulation, except for leaflets, petioles, rachis, stipe, male inflorescences, and fruits (Fig. 1). Over the years, S doses were applied at greater amounts, except in the 3rd year, when there was no application, and in the 8th year with a decrease in the doses applied (Table 2). This fact provided greater S availability in the soil along the years with higher doses of S applied, due to the direct effect of the doses and residual action of previous years (Table 2) and, consequently, greater S absorption by older plants (Fig. 1). In addition, older crops benefit from fertilizer residues of previous years. NG *et al.* (1968) also found an increase in S accumulation in all vegetative organs with increasing age of oil palm plants. Additionally, cultivation of *P. phaseoloides* between the rows of oil palms may have contributed to supply S to oil palm trees. Viégas *et al*. (2021) observed a total cycle of S via *P. phaseoloides* of 10.02 and 0.98 kg ha^{-1}, respectively, at 2 and 8 years of oil palm plantations.

For the reproductive organs (Fig. 1), S showed a behavior similar to that observed for P concentration in male inflorescence of oil palm cultivated in Malaysia (NG *et al*. 1969). In most commercial crops, S and P requirements are considered to be similar (Alvarez *et al*. 2007). The peduncle and spikelets showed an increase in S concentration with plant age (Fig. 3e). The lower S concentrations in reproductive organs of older plants can be explained by yield increase, ranging from 1.5 to 20.0 t ha^{-1} (Table 2), which provides greater S export (Franzini *et al*. 2020).

Therefore, age modifies S dynamics in oil palm plants and thus changes DM production of oil palm trees in the period from 2 to 8 years cultivated in the Amazon region (Viégas *et al*. 2001). Fairhurst and Härdter (2003) detected nutritional differences with palm tree ages, since S accumulation is largely directed to DM production in young leaves. In older palm trees, there is a constant relocation of nutrients to the bunches. This may explain the greater S accumulation in fruits, evidencing the importance of S in production. Furthermore, the increase in S accumulation with plant age is directly linked to the increase in S extraction (Fig. 6c), as this increase may be related to plant growth and crop yield of palm trees.

Sulfur presented the greatest deficiency among the macronutrients evaluated in the Tenera type oil palm and in the cultivar of the interspecific hybrid with Caiaué (HIE OxG) up to 6 years old, regardless of the genotype (Matos *et al*. 2019). The decrease in S concentration may be due to leaching, which commonly occurs in sandy soils and to a high mineralization rate of soil organic matter (Gerendas *et al*. 2009; Vitti *et al*. 2018), under the study conditions (Table 1).

According to Sabir *et al*. (2015), S is essential for oilseeds, as it relates to the formation of organs for fatty acid storage and oil biosynthesis. Therefore, the increase in fruit production is directly linked to the increase in S exports. The amounts of macronutrients exported in oil palms vary according to plant age (Viégas 1993). Sulfur exports by oil palm for the production of fresh fruit bunches in the Eastern Amazon are on average 8.5 kg ha^{-1} (Franzini *et al*. 2020). Thus, it seems that the maximum export of S in the current study (8 kg ha^{-1}; Fig. 5b) is close to the average for the region (Franzini *et al*. 2020). The amount of S immobilized was high, 3.9 times greater than that exported (Fig. 6). Tarmizi and Mohd Tayeb (2006) estimated that P immobilization in oil palm is 26 kg ha^{-1}, a value lower than that found in our study for S immobilized (Fig. 6). This fact may be related to the greater requirement of S in relation to P. Alvarez *et al*. (2007) and Vitti *et al*. (2018) stated that in several commercial crops, S nutritional requirement is greater than P. Viégas (1993) found that S was the least exported nutrient in oil palm trees at different ages.

According to the fertilization recommendation for average yield (17 t ha^{-1}) of oil palm in Eastern Amazon, crop demand is 20 kg ha^{-1} of S, considering a fertilization efficiency of 40% (Franzini *et al*. 2020). Thus, S cycling via vegetative organs (leaflet, petiole, rachis and arrows) seems to provide an average of 36% of the nutrient. These facts highlight the importance of proper management of these plant residues in plantations, as this study indicates the potential for S cycling. According to Homma and Rebello (2020), the Eastern Amazon region is significant regarding the consumption of fertilizers, accounting for 35% of the northern region of Brazil. Possibly, many producers in the region do not supply sufficiently the nutrients by oil palm cycling, in compensation for exports caused by harvest. Producers could reduce the amounts applied in crop fertilization with consequent environmental and economic gains.

Sulfur use efficiency in oil palm plants contributes to the mechanism to increase nutrient accumulation and mainly plant dry matter. This is because increasing nutrient use efficiency is the main strategy used by plants to increase dry matter biosynthesis by reusing nutrients from senescent plant tissues and redirecting them to metabolic pathways for biomass production (Prado 2021). Our results show that oil palm plants increase S use efficiency as a function of plant age to increase their biomass production capacity.

The increase in S use efficiency as a function of plant age promotes changes in the nutritional demand, modifying S accumulation and consequently the dynamics of immobilization, recycling, and export of nutrients (Fig. 6). Furthermore, our results reveal that S use efficiency increases differently in the different organs oil palm, indicating that S use efficiency in the rachis is 2630 times greater than in the cabbage (Fig. 7).

Results showed that the nutritional requirement of S changes according to crop age; therefore, accepting the first hypothesis. Concentrations and accumulations of S change in the different plant organs, impacting on the rates of recycling, immobilization, and exports of S, accepting the second hypothesis. Our results pave the way for further research, showing that nutritional management needs to take into account plant age, ensuring an adequate S supply to the oil palm crop.

Conclusion

The behavior of S in oil palm nutrition in commercial planting in Eastern Amazon was significant in terms of concentration, among several organs, in the palm heart and inflorescences, in relation to accumulation in the stipe and crown organs and in the exports to bunches, due to the increase in plant age. Also, the immobilized and recycled quantity of S was higher than that exported by oil palm. Moreover, the S use efficiency increased proportionally with the age of oil palm plants; however, at different intensities in different plant organs.

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