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Soil Chemical Properties and Production of Physic Nut Intercropped With Forage Plants and Grain Crops

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Abstract

Intercropping cover plants with physic nut (*Jatropha curcas* L.) may be a viable strategy for improving soil quality and sustaining the yield of this oilseed crop. However, one of the main challenges facing prolonged cropping of physic nut is the lack of information regarding the agronomic practices of the crop in intercropping systems. The aim of this study was to evaluate the effect of cropping systems with cover plants and grain crops on the soil chemical properties and cumulative production of physic nut grain and oil. Eleven cropping systems and two evaluations were conducted in a split-plot arrangement on a dystrophic red latosol (*Latossolo Vermelho Distrófico*) in the municipality of Dourados. Growing cover plants or grain crops between the rows of physic nut did not provide significant increases in the cumulative production of grain and of oil over growing physic nut alone. There was reduction in the availability of nutrients, especially P and K, through growing Campo Grande *Stylosanthes*, *U. humidicola*, and *Crotalaria*. However, the beneficial effects of intercropping related to maintaining soil cover and the possibility of increasing the profitability of cropping physic nut from the production of forage crops and grains should be considered. Although the results did not show a significant increase in physic nut production in intercropping systems, the approach still offers opportunities to improve agricultural sustainability, crop diversification, and long-term profitability.

Keywords: *Jatropha curcas* L., cropping systems, grain yield, oil production, nutrient cycling

1. Introduction

Physic nut (*Jatropha curcas* L.) is a species mainly cultivated for its grains or oil seeds whose oil is a raw material for the production of biodiesel (Souza et al. 2013). Although growing physic nut alone has not proven to be economically viable, because of its late fruit production process and low yield (Singh et al., 2019), it is a perennial species with slow initial growth and considerable between-row spacing, a high leaf area index, deciduous habit, and low C/N ratio, traits that are interesting for intercropping with forage plants (Silva et al., 2012; Silva et al., 2015). However, consideration must be made of the effect of intercropped species on the nutritional state and on the grain yield of physic nut under distinct edaphic and climatic conditions (Pacheco et al., 2013). Therefore, more studies are necessary, especially in intercropping systems with physic nut, so as to understand the relationship of the intercropped plants with effects on soil fertility and, consequently, understand the impact of these cropping systems on production of the main crop.

Straw/stover production by cover plants allows accumulation of organic matter on the soil surface, a fundamental factor for the improvement of soil chemical properties, reduction of nutrient losses by erosion, and recycling and gradual provision of nutrients to cultivated crops during the mineralization process (Baumert et al., 2014). In addition, maintenance of crop residues on the surface, along with not turning the soil over with tillage implements, increase the microbial population and activity (Singh et al., 2019) and reduce soil losses by erosion (Wani et al., 2012; Baumert et al., 2014). Growing cover plants with high biomass production capacity, alone or intercropped, is recommended for crop rotation. The selection of plant species for such a purpose depends on characteristics such as the phytomass production potential, the plant growth rate, and the ability of taking up and accumulating nutrients (Wolschick et al., 2016).

Regarding soil conservation, growing cover crop species that have a lower rate of decomposition is useful for maintaining soil protected from erosive agents for a longer time (Baumert et al., 2014) and for promoting temporary immobilization of nutrients in the plant biomass (Ziech et al., 2015). The use of grasses alone as cover crops or of intercropping with grasses has greater potential for soil protection and can contribute at the same time to gradually release of nutrients (Pacheco et al., 2013; Ziech et al., 2015). In this respect, there is the need for finding balance among plant composition, soil protection, and nutrient release, which can be achieved through intercropping with leguminous crops and grasses as cover plants (Perin et al., 2010; Ziech et al., 2015). According to Pacheco et al. (2011, 2013), *U. ruziziensis* plants accumulate from 92.9 to 210.8 kg ha^{-1} of K in the shoots, and the half-life ranges from 9 to 38 days. The tendency toward increase in K availability in the soil in the stubble of *U. ruziziensis*, *U. ruziziensis* + Stylosantes, and 'Massai' can be attributed, according to Pacheco et al. (2011), to greater biomass production capacity and greater soil cover and nutrient cycling of these species, above all of *U. ruziziensis*. However, for full operation of the system, it is important to understand that the accumulation of nutrients and the decomposition of cover plants depend on various factors, such as the species, the fertility of the soil, the phenological stage at the time of management practices, the quantity of phytomass deposited, the C/N and lignin/N ratios, and the sowing time, as well as the climate conditions of each study (Teixeira et al., 2011).

Cover plants residues increase the nutrient supply, especially in the soil surface layers (Pavinato & Rosolem, 2008). That makes it necessary to know the dry matter production and decomposition time of the species to be used in the intercropping system; these aspects directly affect the amount of straw/plant residue on the soil and, subsequently, soil chemical properties. The latters, in turn, directly affect nutrient dynamics in the soil (Ziech et al., 2015). Good results have been obtained among winter cover crops with radishes because of their hardiness, rapid initial development, and short cycle (Crusciol et al., 2005) as well as with pigeon pea and rattlepod because of their abundant root system and biomass production (Silveira et al., 2005). The aim of this study was to evaluate the effect of cropping systems with cover plants and grain production plants on soil chemical properties and the cumulative production of physic nut grain and oil.

2. Method

2.1 Plant Materials

Physic nut (*Jatropha curcas* L.) planting materials obtained from was intercropped with four (*Stylosanthes macrocephala + Stylosanthes capitata*, *Urochloa ruziziensis*, *Urochloa humidicola* and *Panicum maximum* cv. Massai) and two green manure (*Cajanus cajan* and *Crotalaria spectabilis*). Six different crops were involved in the rotation system of intercropped species, *i.e.*, peanut, crambe, cowpea, maize, soybean, and radish. The 11 treatments corresponded to different systems where plant species are intercropped between the physic nut rows as well as the crop rotations for intercropped species and a control (Table 1).

Table 1. Species in intercropping systems with physic nut and physic nut alone

Treatment	Intercropping systems with physic nut
Control	Monoculture of physic nut
Campo Grande Stylosanthes	Intercropping of physic nut with *Stylosanthes macrocephala + Stylosanthes capitata*
Ruziziensis	Intercropping of physic nut with *Urochloa ruziziensis*
Ruziziensis + Stylosanthes	Intercropping of physic nut with *Urochloa ruziziensis* and *Stylosanthes macrocephala + Stylosanthes capitata*.
Humidicola	Intercropping of physic nut with *Urochloa humidicola*
Massai	Intercropping of physic nut with *Panicum maximum* cv. Massai
Dwarf pigeon pea	Intercropping of physic nut with *Cajanus cajan*
Crotalaria	Intercropping of physic nut with *Crotalaria spectabilis*
Rotation 1	Intercropping of physic nut with crop rotation system-1 (peanut/crambe/ cowpea/maize)
Rotation 2	Intercropping of physic nut with crop rotation system-2 (second crop maize/crambe/soybean/peanut)
Rotation 3	Intercropping of physic nut with crop rotation system-3 (cowpea/radish/maize/cowpea)

The experiment was conducted in an experimental area at the Paraíso Farm, district of Itahum, in the municipality of Dourados, Mato Grosso do Sul, Brazil (22º05′44″S, 55º18′48″W; and 484 m altitude). The climate in the region, according to the Köppen-Geiger classification, is Cwa, humid mesothermal, with hot summers and dry winters (Fietz et al., 2017). The low rainfall periods extend from the first decade of June to the second decade of September, and the second decade of August. The high rainfall occurs from October to March, and in December. The mean temperatures in Dourados vary from mean values higher than 20 ºC (August to April) to mean values below 20 ºC (May to July). Highest temperatures predominate in the months of December and January (Fietz et al., 2017) (Figure 1).

The soil of the experimental area a dystrophic red latosol (*Latossolo Vermelho Distrófico*) (Santos et al., 2018) or Oxisol (American Soil Classification) (Soil Survey Staff, 2014), with 200 g kg^{-1} of clay. The material of origin of this soil is weatherized residues of Caiuá Sandstone of the São Bento Series from the Cretaceous Period (Araujo et al., 2004).

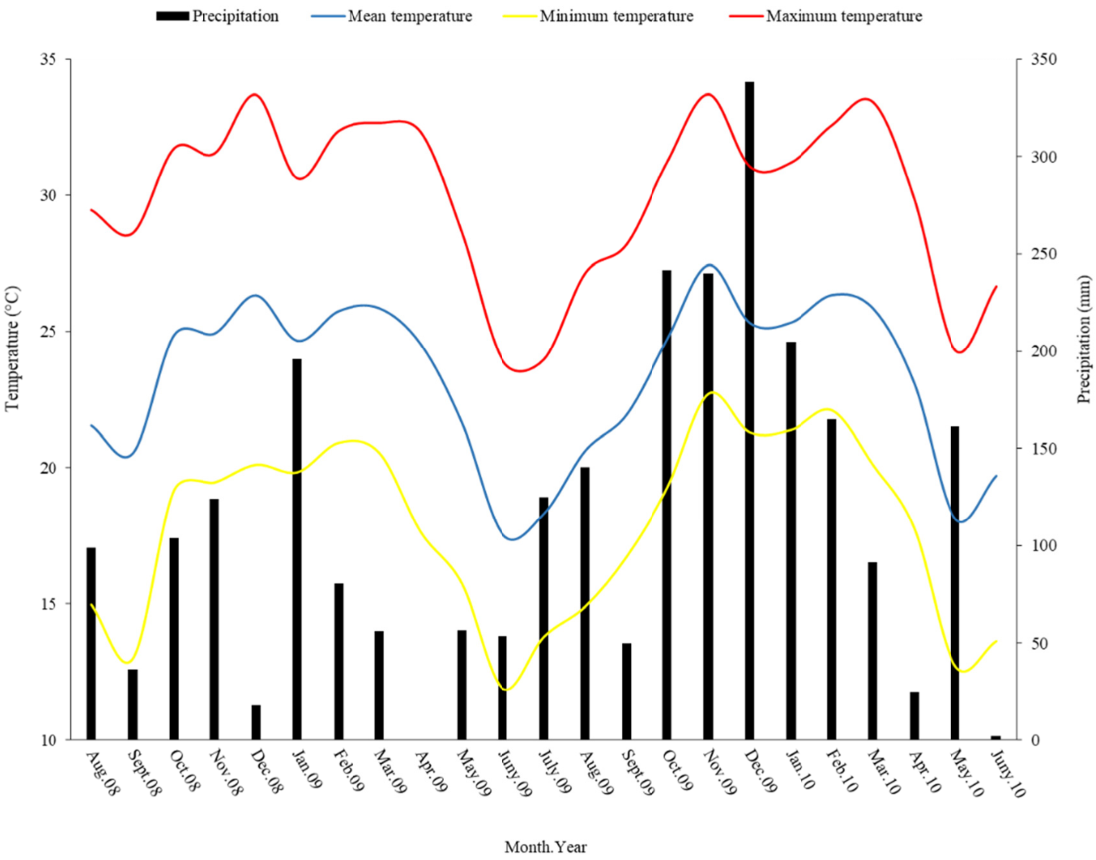

Figure 1. Monthly cumulative rainfall and temperatures in the 2008/2009 and 2009/2010 cropping seasons

Source: Meteorological station of Embrapa Agropecuária Oeste.

The experimental design was a randomized block design arranged in a split-plot with 11 intercropping systems × 2 evaluation times. Physic nut was manually sown in November 2006 at a spacing of 3 × 2 m, for a density of 1,666 plants ha^{-1} (Silva et al., 2013). After emergence, the physic nut was manually thinned, leaving one plant per plant hole (Silva et al., 2015). In the 2006/07 and 2007/08 crop years, the normal crop management practices and treatments for physic nut were used, as described in Silva et al. (2015). The experimental plots were set up in the physic nut crop in the third year in an area of 120 m² (12 × 10 m), consisting of four rows with five plants per row. In the intercropping, plots with forage species were formed by three 8-m-length rows between the physic nut rows. The forage species were grown at a spacing of 0.45 m between rows (Silva et al., 2012). An approximate distance of 0.5 m was maintained at each side of the physic nut row to prevent excessive competition among plants and to facilitate harvest and other crop treatments, as described in Silva et al. (2012). Field upkeep and fertilizer applications in intercropping systems and rotation systems were performed as described by Laviola and Dias (2008), Silva et al. (2012), and Silver et al. (2015). The plant matter resulting from the cutting was uniformly distributed on the plot, remaining on site for purposes of soil cover.

2.2 Plant Parameters Measured

The plot area used for data collection consisted of six plants: three plants in each of the two center rows. Grains of the six physic nut plants were manually collected on per experimental plot basis, put in paper bags and dried in an oven at 55 ºC until reaching constant weight (Horschutz et al., 2012), per 48 hours. The threshing followed and allowed determining the grain dry matter weight and grain yield as described by Silva et al. (2016). Analysis of the physic nut grain oil content was carried out using the Soxhlet extraction method reported by Lara et al. (1985). Cumulative grain yield (kg ha^{-1}) was the sum of the yields of the three cropping seasons 2008/2009, 2009/2010, and 2010/2011 (Figure 2). The mean oil content (%) was average of three cropping seasons mean oil contents. Cumulative oil yield (COY, kg ha^{-1}) was the sum of the oil yields of the three cropping seasons 2008/2009, 2009/2010, and 2010/2011.The oil yield (OY) for the cropping season n (OY$_n$) is formulated as follows:

$$OY_n = GY_n \times OC_n \tag{1}$$

where, OY_n is the oil yield of the cropping season *n*; GY_n is the grain yield of the cropping season *n*; OC_n is the oil content of the grains (or percentage of oil in the grains) of the cropping season *n*.

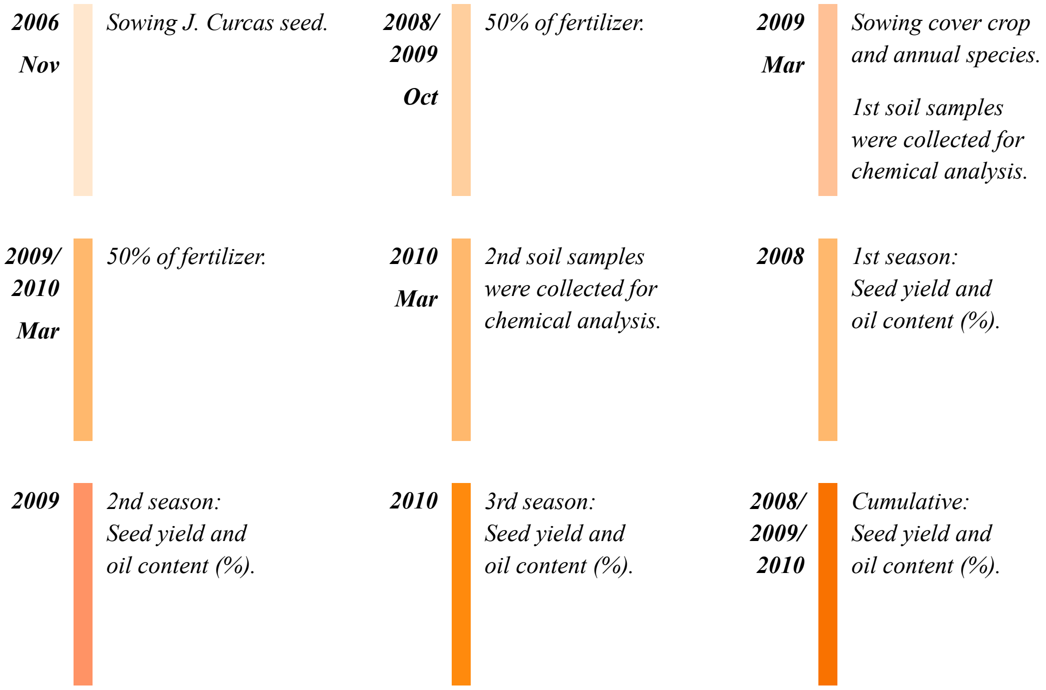

Figure 2. Trial workflow including data collection

The forage and cover crop species were managed by cutting with a backpack brush cutter when the plants reached the grazing height recommended for each species; five cuttings were carried out from April 2009 to March 2010, as described in Silva et al. (2012).

2.3 Soil Sample Collection and Chemical Analysis

For soil chemical analysis, soil samples were collected in each experimental plot in the 0-20 cm and 20-40 cm layers before the sowing of intercropped species in January 2009, 26 months after the sowing of physic nut (26 MAS), and in March 2010 that is 38 months after sowing of physic nut (38 MAS). Therefore, these two soil samplings corresponds to the before cover crops and after cover crops planting. In both evaluations, four single soil samples were taken in each layer using a Dutch auger, at 0.5 m from each plant row. Chemical analyses were performed in the physicochemical analysis laboratory of Embrapa Agropecuária Oeste according to the procedure described by Teixeira et al. (2017). Soil pH, phosphorus, potassium, calcium, magnesium, total carbon were the nutrients quantified.

2.4 Statistical Analysis

The data on the soil chemical properties were analyzed independently for each layer. Analyses of variance were carried out for the pH, organic matter (OM), and each of the contents of P, K, Ca, Mg. Another analyses of variance were performed for the cumulative grain yield and mean oil content and cumulative oil yield contents. Mean values of the cropping systems were compared using Tukey's test. The data was analyzed using the SISVAR® statistical software (Ferreira, 2014).

3. Results and Discussion

3.1 Soil Chemical Properties

The values of pH ($CaCl_2$), in the 0-20 cm layer were not changed by the systems under evaluation (Table 2). These results corroborate those of Wohlenberg et al. (2004), who studied seven cropping systems over six agricultural years and did not find differences among the crops for soil pH. However, between the evaluation times, it was observed that only the Rotation 1 system (peanut/crambe/cowpea/maize) reduced the pH value from 5.3 to 4.88 (Table 2). In addition, in the mean of the cropping systems, a decrease was observed in pH between the first and the second evaluation (performed at 26 MAS and 38 MAS, respectively).

In the 20-40 cm layer, both among the systems and between the evaluation times, there was no significant difference among the treatments (Table 2).

Table 2. pH ($CaCl_2$) in the 0-20 cm and 20-40 cm soil layers under intercropping systems with physic nut in two evaluations: at 26 months after sowing physic nut (26 MAS) and 38 months after sowing physic nut (38 MAS)

Cropping System	pH ($CaCl_2$)					
	Layer (m)					
	0-20 cm		Mean	20-40 cm		Mean
	26 MAS	38 MAS		26 MAS	38 MAS	
Control	5.4 Aa	5.2 Aa	5.3 A	4.6 Aa	4.7 Aa	4.7 A
Stylosanthes	5.1 Aa	5.0 Aa	5.0 A	4.4 Aa	4.5 Aa	4.5 A
Ruziziensis	5.0 Aa	4.9 Aa	5.0 A	4.6 Aa	4.4 Aa	4.5 A
Ruziziensis + Stylosanthes	5.1 Aa	5.2 Aa	5.1 A	4.6 Aa	4.6 Aa	4.6 A
Humidicola	5.1 Aa	5.0 Aa	5.0 A	4.7 Aa	4.5 Aa	4.6 A
Massai	5.2 Aa	5.4 Aa	5.3 A	4.5 Aa	4.6 Aa	4.6 A
Dwarf pigeon pea	5.2 Aa	5.1 Aa	5.2 A	4.6 Aa	4.4 Aa	4.5 A
Crotalaria	5.4 Aa	5.3 Aa	5.3 A	4.7 Aa	4.6 Aa	4.7 A
Rotation 1	5.3 Aa	4.9 Ab	5.1 A	4.6 Aa	4.5 Aa	4.6 A
Rotation 2	5.2 Aa	5.0 Aa	5.1 A	4.7 Aa	4.5 Aa	4.6 A
Rotation 3	5.4 Aa	5.0 Aa	5.2 A	4.7 Aa	4.5 Aa	4.6 A
Mean	5.2 a	5.1 a		4.6 a	4.6 a	

Note. Mean values followed by the same uppercase letters in the column comparing treatments (cropping systems) in each evaluation, and the same lowercase letters in the row comparing evaluations of a treatment are not significantly different based on Tukey's test at 5% probability.

Regarding organic matter content in the 0-20 cm and 20-40 cm layers, no significant difference was observed among the at 26 MAS, which indicates that there was homogeneity in the experimental area before setting up the cropping systems. However, in the two layers evaluated, a significant increase was observed in the organic matter content between the two evaluation times, considering the mean of the cropping systems (Table 3).

Table 3. Organic matter (OM) content in the 0-20 cm and 20-40 cm soil layers under intercropping systems with physic nut in two evaluations: at 26 MAS and 38 38 MAS

Cropping system	OM (g kg^{-1})					
	Layer (m)					
	0-20 cm		Mean	20-40 cm		Mean
	26 MAS	38 MAS		26 MAS	38 MAS	
Control	13.5 Aa	15.0 Aa	14.2 A	12.4 Aa	12.8 Aa	12.6 A
Stylosanthes	13.4 Aa	13.0 Aa	13.2 A	11.2 Aa	12.9 Aa	12.0 A
Ruziziensis	13.5 Aa	14.6 Aa	14.0 A	9.5 Aa	11.8 Aa	10.7 A
Ruziziensis + Stylosanthes	12.0 Aa	15.2 Aa	13.7 A	9.0 Ab	12.8 Aa	10.9 A
Humidicola	13.8 Aa	14.5 Aa	14.2 A	7.7 Aa	12.3 Aa	10.0 A
Massai	11.9 Aa	14.2 Aa	13.1 A	9.6 Aa	11.5 Aa	10.5 A
Dwarf pigeon pea	13.7 Aa	14.1 Aa	13.9 A	10.9 Aa	12.9 Aa	11.9 A
Crotalaria	11.6 Aa	13.0 Aa	12.3 A	10.5 Aa	12.2 Aa	11.4 A
Rotation 1	11.7 Aa	13.8 Aa	12.7 A	8.5 Aa	11.0 Aa	9.7 A
Rotation 2	13.6 Aa	13.2 Aa	13.4 A	9.7 Aa	11.6 Aa	10.7 A
Rotation 3	12.1 Aa	13.4 Aa	12.8 A	11.2 Aa	12.9 Aa	12.0 A
Mean	12.8 b	14.0 a		10.0 b	12.2 a	

Note. Mean values followed by the same uppercase letters in the column comparing treatments (cropping systems) at each evaluation period, and the same lowercase letters in the row, comparing evaluations of a treatement are not significantly different based on Tukey's test at 5% probability.

In the 20-40 cm layer, significant differences were not found among the cropping systems (Table 3). It was expected that the effects of the evaluation time would occur in a more pronounced manner in the surface layer through maintaining plant biomass on the soil under conservationist management systems (Brown et al., 2018). However, an increase in organic matter content was observed between the first and the second evaluation in the intercropping systems with *U. ruziziensis* + *Stylosanthes* and with *U. humidicola* (Table 3). This effect occurred at a magnitude that contributed above all to detection of statistical significance for the mean effect of evaluation time in the eleven treatments.

Nutrient recycling is indispensable for sustainability of the system, and a deeper root system of forage crops allows more efficient cycling of nutrients (Perin et al., 2010). It should be emphasized that grasses alone or intercropped with leguminous plants show greater potential for soil protection through their residues remaining on the surface for a longer time (Pacheco et al., 2013; Ziech et al., 2015), which favors phytomass production and nutrient cycling (Pacheco et al., 2013), as well as maintenance of and/or increase in organic C in the soil surface layer (Brown et al., 2018).

The differences found in relation to organic matter content for the same species in different crop years can be attributed to the intrinsic characteristics of the crop residues themselves, as well as the edaphic and climatic conditions, which shows the importance and the need for specific studies in different regions (Ziech et al., 2015).

Wani et al. (2012) found significant increases in C (305 kg ha^{-1} year^{-1}) in the soil after one year of growing of physic nut. They emphasized that a crop of three to five years of age adds around 4,000 kg of plant biomass per year per hectare, equivalent to 1,450 kg C ha^{-1} including 800 kg C ha^{-1} through leaves and 150 kg C ha^{-1} through pruning of branches. In fact, significant additions of C and the activity of live roots under physic nut increased the microbial population, the respiration rate, and the soil microbial biomass.

In regard to soil phosphorus content, differences among the cropping systems were not observed in the 0-20 cm layer (Table 4). Growing the Campo Grande *Stylosanthes* and *U. humidicola* species resulted in considerable reduction in available P content (from 14.93 to 6.85 mg dm^{-3} and from 14.50 to 4.60 mg dm^{-3} of P, respectively) between the first and the second evaluation. Foloni et al. (2008) evaluated the P extracting capacity of soybean, maize, and *U. brizantha* and highlighted that the last species has greater efficiency in taking up P per unit of phytomass produced. The authors commented that, in general, this is a characteristic of brachiaria grasses and that this may be associated with high adaptability to tropical soils, as was found for *U. brizantha* cv. Marandu. That makes this tropical grass a considerable alternative for composing crop rotation programs, aiming at obtaining greater rates of utilization of natural phosphates and of P recycling. According to Collier et al. (2018), the increase in P availability in the soil is due to release of the nutrient accumulated in plant shoots, and also of release of organic compounds during decomposition of the plant residue, which interact with the solid phase of the soil, occupying adsorption sites of anionic nutrients.

Pacheco et al. (2011, 2013) evaluated dry matter production and nutrient cycling by *U. ruziziensis* sown in two locations, both on *Latossolo Vermelho Distroférrico*, and found accumulation of P in plant shoots ranging from 10.4 to 43.8 kg ha^{-1} at the time of management with glyphosate. According to these authors, the half-life for P ranged from 24 to 93 days, and these differences were explained by the edaphic and climatic conditions of each location. The *U. ruziziensis* species shows high rates of decomposition and release of nutrients from the phytomass, due to its low lignin and cellulose content, at 3.67 and 10.95%, respectively (Carvalho et al., 2011). Specifically, P is released more rapidly than Ca because most of its content in found within the vacuole, in mineral form, with high solubility in water. Yet, the release rate is lower than that of K because there are less soluble forms of P (nucleic acids, phospholipids, and phosphoproteins), which are dependent on the microbial population for their mineralization (Pacheco et al., 2013).

Table 4. Phosphorus content available in the 0-20 cm and 20-40 cm soil layers under intercropping systems with physic nut in two evaluations at 26 MAS and 38 MAS

Cropping system	P (mg dm^{-3})					
	Layer (m)					
	0-20 cm		Mean	20-40 cm		Mean
	26 MAS	38 MAS		26 MAS	38 MAS	
Control	10.3 Aa	7.2 Aa	8.8 A	5.8 Aa	3.4 Aa	4.6 A
Stylosanthes	14.9 Aa	6.8 Ab	10.9 A	7.6 Aa	3.4 Ab	5.5 A
Ruziziensis	7.8 Aa	6.6 Aa	7.2 A	4.2 Aa	3.9 Aa	4.1 A
Ruziziensis + Stylosanthes	6.6 Aa	7.8 Aa	7.2 A	3.0 Aa	4.9 Aa	3.9 A
Humidicola	14.5 Aa	4.6 Ab	9.6 A	4.1 Aa	2.7 Aa	3.4 A
Massai	7.5 Aa	9.0 Aa	8.2 A	4.9 Aa	5.6 Aa	5.2 A
Dwarf pigeon pea	7.5 Aa	6.0 Aa	6.8 A	3.6 Aa	3.5 Aa	3.5 A
Crotalaria	9.6 Aa	10.2 Aa	9.9 A	3.6 Aa	6.0 Aa	4.8 A
Rotation 1	9.2 Aa	6.9 Aa	8.0 A	6.0 Aa	4.1 Aa	5.0 A
Rotation 2	9.5 Aa	9.5 Aa	9.5 A	5.4 Aa	4.7 Aa	5.1 A
Rotation 3	15.4 Aa	13.0 Aa	14.2 A	6.2 Aa	5.8 Aa	6.0 A
Mean	10.2 a	8.0 b		4.9 a	4.4 a	

Note. Mean values followed by the same uppercase letters in the column, comparing treatments (cropping systems) at each evaluation period, and the same lowercase letters in the row, comparing evaluations of a treatment are not significantly different based on Tukey's test at 5% probability.

In the 20-40 cm layer, the P content did not differ statistically for the species in the two evaluations; however, P decreased over time when Campo Grande *Stylosanthes* was grown (Table 4). This tendency of decrease in phosphorus availability in the two layers in the Campo Grande *Stylosanthes* cropping system may be related to immobilization of this nutrient, as it showed less mineralization in relation to other systems. Maluf et al. (2015) evaluated the decomposition and mineralization of crop residues and found that the mineralized amount of N, P, K, Ca, Mg, and S is directly proportional to their respective initial content in the residues, and the P mineralization process is regulated by the C/P ratio, where a value greater than or equal to 300 tends toward immobilization and less than 200 favors mineralization. Furthermore, growing Campo Grande *Stylosanthes* was associated with P recycling capacity, which in intercropping can result in a significant increase in grass performance (Souza et al., 2016).

The K content did not differ among the intercropping systems in either of the soil layers evaluated (Table 5). In the 0-20 cm layer, there was a tendency toward reduction in availability of K in the soil from the first to the second evaluation, except in the treatments of *U. ruziziensis*, *U. ruziziensis* + *Stylosantes*, and 'Massai'; and statistically significant differences were found only for Rotation 1 and *Crotalaria* (Table 5). This result is apparently related to the fact of potassium being readily released from the plant tissue of the residues deposited on the soil surface, since this nutrient is not a structural component of the cell wall and does not form organic compounds. As soil samples were collected at approximately 20 days after management of the cover plants and there was a considerable volume of rainfall in the period (Figure 2, March/2010), greater leaching of the nutrient to the soil layer deeper than 40 cm may have occurred. According to Pacheco et al. (2011, 2013), *U. ruziziensis* plants accumulate from 92.9 to 210.8 kg ha^{-1} of K in the shoots, and the half-life ranges from 9 to 38 days. The tendency toward increase in K availability in the soil in the stubble of *U. ruziziensis*, *U. ruziziensis* + *Stylosantes*, and 'Massai' can be attributed, according to Pacheco et al. (2011), to greater biomass production capacity and greater soil cover and nutrient cycling of these species, above all of *U. ruziziensis*.

Table 5. Potassium content in 0-20 cm and 20-40 cm soil layers under intercropping systems with physic nut in two evaluations at 26 MAS and 38 MAS

Cropping system	K (mg dm^{-3})					
	Layer (m)					
	0-20 cm		Mean	20-40 cm		Mean
	26 MAS	38 MAS		26 MAS	38 MAS	
Control	58.7 Aa	39.1 Aa	48.9 A	27.4 Aa	27.4 Aa	27.4 A
Stylosanthes	58.7 Aa	39.1 Aa	48.9 A	23.5 Aa	27.4 Aa	25.4 A
Ruziziensis	50.8 Aa	58.7 Aa	54.8 A	23.5 Aa	23.5 Aa	23.5 A
Ruziziensis + Stylosanthes	58.7 Aa	70.4 Aa	64.6 A	27.4 Aa	39.1 Aa	33.2 A
Humidicola	58.7 Aa	39.1 Aa	48.9 A	27.4 Aa	19.6 Aa	23.5 A
Massai	50.8 Aa	58.7 Aa	54.8 A	27.4 Aa	23.5 Aa	25.4 A
Dwarf pigeon pea	58.7 Aa	39.1 Aa	48.9 A	27.4 Aa	31.3 Aa	29.4 A
Crotalaria	78.2 Aa	39.1 Ab	58.6 A	31.3 Aa	23.5 Aa	27.4 A
Rotation 1	58.7 Aa	31.3 Ab	45.0 A	27.4 Aa	43.0 Aa	35.2 A
Rotation 2	58.7 Aa	39.1 Aa	48.9 A	31.3 Aa	27.4 Aa	29.4 A
Rotation 3	70.4 Aa	50.8 Aa	60.6 A	27.4 Aa	39.1 Aa	33.2 A
Mean	58.7 a	46.9 b		27.4 a	27.4 a	

Note. Mean values followed by the same uppercase letters in the column, comparing treatments (cropping systems) at each evaluation period, and the same lowercase letters in the row, comparing evaluations of a treatment are not significantly different based on Tukey's test at 5% probability.

The reduction in the exchangeable content of K after growing *Crotalaria* is apparently related to the large accumulation of this nutrient in the shoots (199 kg ha^{-1} of K), especially in the plant stems (187 kg ha^{-1} of K, corresponding to 94% of the total), as found by Barbosa et al. (2020) in a *Latossolo Vermelho Distroférrico* in Dourados, MS. Yet, although the nutrient is readily released from the plant tissue, the high accumulation in the stems may have resulted in release of only part of the K in the period of twenty days that passed between management of the plants and collection of soil samples. In the same way, although the Campo Grande *Stylosanthes* showed accumulation from 57 to 60 kg ha^{-1} of K in the shoots, as found by Collier et al. (2018) and Teodoro et al. (2011), an expressive part of this amount is accumulated in the stems. In regard to reduction in K availability in the soil, this result under the Rotation 1 system might be associated with greater export of this nutrient in the peanut crop, as found by Feitosa et al. (1993). According to these authors, in the mean of four cultivars, 24.48 kg ha^{-1} of K is exported upon harvest of peanut pods and seeds. Considering that 1 kg ha^{-1} corresponds to 0.5 mg dm^{-3}, which means that export of K by peanut harvest alone would be responsible for extraction of 12.24 mg dm^{-3} of K from the soil. Despite this, intercropping leguminosae *Cajanus cajan* cv. Anão and *Crotalaria* with physic nut showed intermediary result in terms of seed yield, which was attribute to lower interspecific competition with physic nut and maybe biologic nitrogen fixation available for physic nut.

Comparing the cropping systems in the 0.00 to 0.20 m layer, only the Campo Grande *Stylosanthes* species showed differences in Ca content between the two evaluations, with the highest value observed in the first evaluation (Table 6). In the 0.20 to 0.40 m layer, there was no effect of the cropping systems; however, there was an increase in Ca over time in the system with *Crotalaria*. According to Dalla Côrt et al. (2021), grasses or perennial plants with shrub architecture have greater accumulation of Ca in the shoots because of greater demand for this nutrient in composition of the middle lamella and formation of the cell wall, which results in rigidity in stems or stalks.

Table 6. Calcium content in the 0-20 cm and 20-40 cm soil layers under intercropping systems with physic nut in two evaluations at 26 MAS38 MAS

Cropping system	Ca (cmol$_c$ dm^{-3})					
	Layer (m)					
	0-20 cm		Mean	20-40 cm		Mean
	26 MAS	38 MAS		26 MAS	38 MAS	
Control	2.2 ABa	2.1 Aa	2.1 A	0.8 Aa	0.9 Aa	0.9 A
Stylosanthes	2.8 Aa	1.8 Ab	2.3 A	0.6 Aa	0.8 Aa	0.7 A
Ruziziensis	1.9 ABa	1.7 Aa	1.8 A	0.8 Aa	0.8 Aa	0.8 A
Ruziziensis + Stylosanthes	1.4 ABa	1.5 Aa	1.4 A	0.7 Aa	0.8 Aa	0.8 A
Humidicola	1.8 ABa	1.6 Aa	1.7 A	1.0 Aa	0.8 Aa	0.9 A
Massai	1.2 Ba	2.0 Aa	1.6 A	0.7 Aa	0.9 Aa	0.8 A
Dwarf pigeon pea	1.8 ABa	1.9 Aa	1.9 A	0.6 Aa	0.8 Aa	0.7 A
Crotalaria	1.6 ABa	2.1 Aa	1.9 A	0.7 Ab	1.0 Aa	0.9 A
Rotation 1	2.1 ABa	1.6 Aa	1.8 A	0.9 Aa	0.9 Aa	0.9 A
Rotation 2	1.5 ABa	1.8 Aa	1.7 A	0.8 Aa	1.0 Aa	0.9 A
Rotation 3	1.6 ABa	1.2 Aa	1.4 A	0.9 Aa	0.9 Aa	0.9 A
Mean	1.8 a	1.8 a		0.8 b	0.9 a	

Note. Mean values followed by the same uppercase letters in the column, comparing treatments (cropping systems) at each evaluation period, and the same lowercase letters in the row, comparing evaluations of a treatment are not significantly different based on Tukey's test at 5% probability.

In regard to Mg, for Campo Grande *Stylosanthes*, there was a reduction in availability in the soil from the first to the second evaluation in the 0-20 cm layer (Table 7), similar to what was found for Ca (Table 6). According to Collier et al. (2018), Campo Grande *Stylosanthes* plants evaluated in two cuttings over a 170-day growing period accumulated 133.7 and 45.1 kg ha^{-1} of Ca and Mg in the shoots, respectively. However, it should be noted that these amounts extracted are not enough to result in reduction in the availability of these nutrients in the soil. Considering that 1 cmol$_c$ dm^{-3} of Ca and of Mg are equivalent to 400 and 243.1 kg ha^{-1} of Ca and Mg, respectively, their extraction in the shoots of Campo Grande *Stylosanthes* would result in a decline of only 0.334 and 0.186 cmol$_c$ dm^{-3} of Ca and of Mg in a 0.20-m-depth layer.

Table 7. Magnesium content in the 0-20 cm and 20-40 cm soil layers under intercropping systems with physic nut in two evaluations: at 26 months after sowing physic nut (26 MAS) and 38 months after sowing physic nut (38 MAS)

Cropping system	Mg (cmol$_c$ dm^{-3})					
	Layer (m)					
	0-20 cm		Mean	20-40 cm		Mean
	26 MAS	38 MAS		26 MAS	38 MAS	
Control	1.2 Aa	1.1 Aa	1.1 A	0.6 Aa	0.6 Aa	0.6 A
Stylosanthes	1.5 Aa	1.0 Ab	1.3 A	0.4 Aa	0.6 Aa	0.5 A
Ruziziensis	1.0 Aa	0.9 Aa	0.9 A	0.6 Aa	0.5 Aa	0.5 A
Ruziziensis + Stylosanthes	0.8 Aa	0.8 Aa	0.8 A	0.5 Aa	0.6 Aa	0.5 A
Humidicola	1.0 Aa	0.9 Aa	0.9 A	0.6 Aa	0.5 Aa	0.6 A
Massai	0.8 Aa	1.1 Aa	0.9 A	0.5 Aa	0.6 Aa	0.6 A
Dwarf pigeon pea	1.0 Aa	1.0 Aa	1.0 A	0.4 Aa	0.5 Aa	0.4 A
Crotalaria	0.9 Aa	1.2 Aa	1.0 A	0.5 Ab	0.7 Aa	0.6 A
Rotation 1	1.1 Aa	0.8 Aa	1.0 A	0.6 Aa	0.6 Aa	0.6 A
Rotation 2	0.9 Aa	0.9 Aa	0.9 A	0.6 Aa	0.5 Aa	0.6 A
Rotation 3	1.1 Aa	0.7 Aa	0.9 A	0.6 Aa	0.6 Aa	0.6 A
Mean	1.0 a	1.0 a		0.5 a	0.6 a	

Note. Mean values followed by the same uppercase letters in the column, comparing treatments (cropping systems) at each evaluation period, and the same lowercase letters in the row, comparing evaluations of a treatment are not significantly different based on Tukey's test at 5% probability.

In the 20-40 cm layer, an increase in the Mg content in the soil was observed for *Crotalaria* from the first to the second evaluation (Table 7), just as occurred for Ca in the same soil layer (Table 6). These results are in agreement with those obtained by Perin et al. (2010), who found that growing *Crotalaria* provided for rapid release of Mg, from seven to eight days, which was a result of the participation of this element in ionic compounds and soluble molecules. Maluf et al. (2015) emphasize that 70% of the Mg is easily released and that the remaining 30% is mineralized in a gradual manner, depending on decomposition, as it is part of structural components of plants.

In general, the cropping systems evaluated had little effect on the soil chemical properties in the period evaluated. Although statistically significant changes in pH in $CaCl_2$ and changes in organic matter and nutrient contents were occasionally found in some cropping systems, they tended to occur in small magnitude. Except for phosphorus and potassium, the changes observed were not very expressive in terms of increasing or decreasing soil fertility, especially for growing physic nut, for which there are no nutrient sufficiency ranges established. In this study, there was pronounced reduction in P availability through growing Campo Grande *Stylosanthes* (in both soil layers evaluated) and *U. humidicola* (only in the 0-20 cm layer). There was also considerable reduction in availability of K through growing *Crotalaria* and the component species of Rotation 1 (only in the uppermost layer). However, it should be emphasized that the immobilization of nutrients in the crop residues is temporary, since these nutrients will be released to the soil as decomposition of the plant tissues occurs. Specifically for phosphorus, temporary immobilization in the organic form in the plant residues may even be beneficial for increasing efficiency in use of this nutrient; it avoids the formation of non-labile forms, which are characterized by restricted reversibility to the labile forms (Novais and Smyth, 1999). For potassium, immobilization of the nutrient in fibrous plant tissues (stems) of C*rotalaria* may also make it possible to minimize losses by leaching, since release to the soil will occur in a gradual manner. Therefore, there reduction in the availability of nutrients, especially P and K, through growing Campo Grande *Stylosanthes*, *U. humidicola*, and *Crotalaria*, resulting from temporary immobilization of the nutrients in the crop residues.

The limited expressiveness of the effects of the intercropping systems on the soil chemical properties may be related to the short period of time (twelve months) between the two soil samplings so as to allow evaluation of the effect of plant biomass in a single crop cycle. Moreover, it should be emphasized that physic nut is characterized by leaf senescence and abscission in the driest and coldest periods of the year. As of the third crop year, there may be deposition of 1,216 kg ha^{-1} of dry phytomass, with recycling of around 1.5, 15, 23, and 14 kg ha^{-1} of P, K, Ca, and Mg, respectively (Kurihara et al., 2016). And as the plant canopy of adult physic nut plants nearly covers all the space between the crop rows, a relatively uniform distribution of this dry phytomass is expected, to minimize part of the effects of accumulation and release in the phytomass of the plants grown in the different intercropping systems.

3.2 Cumulative Grain and Oil Yields of Jatropha curcas

The effect of the systems with forage and grain producing crops intercropped with physic nut in three crop years was observed on cumulative grain yield, mean oil content, and cumulative oil yield (Table 8).

Smaller cumulative yields of physic nut grain were found in intercropping in the systems with *U. ruziziensis*, *U. ruziziensis* + *Stylosanthes*, 'Massai', and *U. humidicola*; intermediate cumulative grain yields were found with Campo Grande *Stylosanthes*, *Crotalaria*, the Rotation 1 system, dwarf pigeon pea, and the Rotation 3 system. In contrast, the following stood out with higher cumulative grain yields: physic nut (alone) and the Rotation 2 system; however, they only differed from *U. ruziziensis*, *U. ruziziensis* + *Stylosanthes*, 'Massai', and *U. humidicola*.

This reduction in cumulative grain yields of physic nut in the intercropped system may be attributed to competition for water, light, and nutrients (Silva et al., 2015; Silva et al., 2016). In contrast, in the Rotation 2 system, the highest cumulative grain yield of physic nut (1,012 kg ha^{-1}) was observed, although it is statistically similar to that obtained for physic nut alone (947 kg ha^{-1}). This yield potential is in agreement with results obtained by Maftuchah et al. (2020) upon evaluating the performance of 6 cultivars over 5 crop years. However, soil properties can affect physic nut grain yield, which may result in high diversity of grain production in different regions (Silva et al., 2016). It should be emphasized that there are various factors that affect the level of physic nut production, and the most dominant are altitude and yearly rainfall. Rainfall is the most important factor in growing physic nut; the rainfall level adequate for growing this crop is around 300-1,000 mm year^{-1} (Maftuchah et al., 2020). Nevertheless, that did not represent a limiting factor during the period of conducting this study (Figure 2).

Table 8. Mean values of cumulative grain yield, mean oil content, and cumulative oil yield in the different intercropping systems with physic nut in the 2008/2009, 2009/2010, and 2010/2011 crop years

Cropping system	Cumulative grain yield		Mean oil content		Cumulative oil yield	
	kg ha^{-1}		%		kg ha^{-1}	
Control	947	AB	28.6	F	272	AB
Stylosanthes	712	ABCD	31.4	CDE	228	AB
Ruziziensis	576	D	36.0	A	211	AB
Ruziziensis + Stylosanthes	660	BCD	32.8	BCD	217	AB
Humidicola	612	CD	33.8	ABC	213	AB
Massai	585	D	34.8	AB	204	B
Dwarf pigeon pea	738	ABCD	33.8	ABC	247	AB
Crotalaria	775	ABCD	32.7	BCD	254	AB
Rotation 1	799	ABCD	33.0	BCD	264	AB
Rotation 2	1012	A	30.5	DEF	300	A
Rotation 3	923	ABC	29.8	EF	275	AB
Mean	758		32.5		244	

Note. The mean values in a column followed by the same letter do not differ from each other based on Tukey's test ($p \leq 0.05$).

The highest yield of physic nut, achieved in the Rotation 2 system, may be due to less competition with the maize crop in the summer, which had low biomass accumulation and grain yield, resulting from competition for light when intercropped with physic nut at a spacing of 3 × 2 m (Silva et al., 2015).

Regarding mean oil content in the three crop years, higher values can be observed in the intercropped systems, which tended to have lower cumulative grain yields of physic nut in some systems (*U. ruziziensis*, *U. humidicola*, and 'Massai'). In contrast, other cropping systems (Rotation 3, Rotation 2, and the Control) exhibited an opposite tendency, with lower mean oil content associated with higher yields, corroborating Silva et al. (2016). This inversely proportional response between grain yield and mean oil content is in agreement with Maftuchah et al. (2020), who studied two production environments over five crop years; they found lower grain yield and higher mean oil content in the driest environment, whereas in the wettest environment, the opposite was observed. In the latter, a mean oil content of 30.7% was found, and in the former, mean oil content was 35.5%, values which were similar to those obtained in the present study. Silva et al. (2016) found mean oil content of the physic nut grain of 33.24%, 34.84%, and 29.37% in the 2008/2009, 2009/2010, and 2010/2011 crop years, respectively. Singh et al. (2016), in turn, found 27.68% to 37.49% oil content in physic nut grain.

Analysis of cumulative oil yield over three crop years showed the effect of the cropping systems, with the highest value for the Rotation 2 system. However, there was a significant difference only when compared to intercropping with 'Massai'. This can be attributed to the fact of 'Massai' exhibiting greater yield capacity and tolerance to shading than the other species when intercropped with physic nut (Silva et al., 2012); it therefore competes with physic nut.

It should be emphasized that even though growing cover plants and/or grain producing plants may have reduced cumulative grain and oil production by physic nut plants in a statistically significant way, it is necessary to consider the beneficial effects related to maintenance of soil cover. Growing species between the rows protects the soil against erosive effects of the impact of raindrops; it maintains milder and more stable temperatures on the soil surface; it improves soil physical and biological properties, resulting from the phytomass production of the root system; and it increases efficiency in the use of nutrients (through temporary immobilization in the crop residues and recovery of leached elements at depth), as mentioned by Forte et al. (2018), Luo et al. (2020), and Dalla Côrt et al. (2021). Two other important benefits of interspersed growing are the possibility of integration with livestock activity through grazing of the forage species (grasses and/or leguminous plants) and grain/seed production (peanut, cowpea, maize, and/or soybean), which may result in an increase in the profitability of the physic nut crop.

4. Conclusions

The study findings underscored that the growing cover plants or grain producing plants between the physic nut rows did not lead to significant increases in cumulative grain and oil production in physic nut plants compared to growing physic nut alone. There was reduction in the availability of nutrients, especially P and K, through growing Campo Grande *Stylosanthes*, *U. humidicola*, and *Crotalaria*. However, consideration should be made of the beneficial effects related to maintenance of soil cover and to the possibility of increasing the profitability of the physic nut crop as a result of grazing of the forage plants and of grain production.

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