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Evaluation of perennial herbaceous legumes with different phosphorus sources and levels in a Brazilian Ultisol

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Abstract

This study was carried out under field conditions with the aim of evaluating the period of time necessary for soil cover, dry matter production and accumulation of nutrients by perennial herbaceous legumes with different phosphorus sources at different levels. Four legumes were evaluated: calopo (*Calopogonium mucunoides* Desv.), forage groundnut (*Arachis pintoi* Krap. & Greg.), siratro (*Macroptilium atropurpureum* (OC.) Urb.) and tropical kudzu (*Pueraria phaseoloides* (Roxb.) Benth.). Each of these species received different phosphorus (P) sources and levels: no phosphate fertilization; 44 and 88 kg of P ha^{-1} applied as rock phosphate; and 44 kg of P ha^{-1} as triple superphosphate. Calopo, siratro and tropical kudzu completely covered the soil surface 129 days before forage groundnut. Phosphate fertilization did not increase the dry matter production of any species. The legumes forage groundnut, siratro and tropical kudzu showed desirable characteristics that promote their use as cover crops, such as high dry matter production and shoot accumulation of nitrogen (N) and potassium (K). Forage groundnut had the highest proportion of N derived from the atmosphere at the end of the rainy season, while there were no significant differences between the legumes at the end of the dry season. There was an elevation of soil pH and calcium + magnesium (Ca + Mg) contents, associated with a reduction of aluminum (Al) content, in the surface soil layer (0–5 cm) for siratro in relation to groundnut and tropical kudzu. Tropical kudzu promoted higher soil organic C contents when compared to groundnut.

Key words: biological nitrogen fixation, cover crops, phosphate fertilization

Introduction

The use of cover crops is indicated as a strategy to improve sustainability of agroecosystems, bringing benefits to both soil and crops[1]. Gliessman[2] affirmed that some cover crops may cause favorable impacts on soil structure, soil fertility and pest control, reducing the use of external inputs in agriculture. On the other hand, problems such as the increase of certain pests, like nematodes, have also been related to some cover crops[3,4]. Some characteristics are desirable for cover crops used in tree-based systems, such as improvement of crop yields; reduction of soil erosion; increase of soil organic matter, supply of nitrogen and retention of other nutrients in the soil; inhibition of weeds and suppression of pest organisms[2]. Among the plant species employed, perennial herbaceous legumes intercropped with fruit trees present great potential for improving plant production in orchards[5,6].

Perennial herbaceous legumes, which fix atmospheric nitrogen biologically, represent a strategy to recuperate degraded lands of farmers who cannot afford N fertilizers[7]. Another advantage to soil fertility brought by these plants is related to recycling of nutrients that have been leached to deep soil layers[1]. These nutrients may be absorbed by legume roots, becoming available to cultivated plants after cutting of the cover crops.

Soil covered by perennial herbaceous legumes is generally more protected against erosion[8]. This is due to the mechanical protection promoted by these cover crops, which reduces the direct impact of rain drops on the soil surface. Besides reducing erosion, perennial herbaceous legumes may also increase water infiltration in the soil[9].

Weeds cause negative effects on agriculture in many tropical areas, reducing yields. Cover crops may also allow weed control by competing for light[2], water and nutrient resources[10] or by allelopathic processes[11]. However, studies also indicate that some perennial herbaceous legumes may compete for water and nutrients with fruit crops, suppressing their yields[12].

Besides intercropping with fruit trees, perennial herbaceous legumes have also been used successfully as forage plants[13,14]. According to this information, plants cultivated as cover crops can also be managed by removing residues for animal feeding. It is important to understand the effects of this type of residue management on soil fertility.

In spite of the described advantages, using inappropriate species for certain soil and climatic conditions may compromise the efficiency of cover crops. Problems such as plant sensitivity to soils with low fertility are described by several authors[15]. Therefore, selecting legumes adapted to soils of low fertility is important in many tropical areas. It is equally important to consider the compatibility of the species within diverse production systems.

The process of biological nitrogen fixation requires high quantities of phosphorus (P)[16]. Consequently, phosphate fertilization represents a strategy to favor legume growth and nitrogen accumulation if the soil is P limited.

The purpose of this study was to characterize the speed with which four different perennial legumes covered the soil, their dry matter production and accumulation of nutrients in the shoot tissue, when fertilized with different phosphorus sources and at different levels. Their N fixation potential and effects on soil fertility were also evaluated, as well as the impacts of different types of residue management.

Materials and Methods

The trial was conducted on an Ultisol located at the Embrapa Agrobiologia Experimental Station, in Seropédica, Rio de Janeiro state, Brazil (longitude 43°41′W, latitude 22°45′S, 33 m above sea level). Soil chemical properties (0–20 cm depth) were analyzed following Embrapa methodology[17], showing pH (H_2O) = 5.6, exchangeable aluminum (Al; titration against NaOH) = 0.0 $\text{cmol}^{(+)}\ \text{dm}^{-3}$, exchangeable calcium (Ca; titration against EDTA) = 3.0 $\text{cmol}^{(+)}\ \text{dm}^{-3}$, exchangeable magnesium (Mg; titration against EDTA) = 1.4 $\text{cmol}^{(+)}\ \text{dm}^{-3}$, available phosphorus (P; Mehlich 1) = 2.0 mg dm^{-3}, exchangeable potassium (K) = 72 mg dm^{-3}. The annual means of temperature and rainfall were 24.1°C and 1620 mm, respectively. The dry season occurs from April to September.

A randomized complete block design was used, with three replicates, in a factorial scheme 4 × 4 (4 legumes and 4 phosphorus sources and levels), in a split-plot experiment. The main plots received legumes [calopo (*Calopogonium mucunoides* Desv.), forage groundnut (*Arachis pintoi* Krap. & Greg.), siratro (*Macroptilium atropurpureum* (OC.) Urb.) and tropical kudzu (*Pueraria phaseoloides* (Roxb.) Benth.)], and treatments with different phosphorus sources and levels (no phosphate fertilization, 44 and 88 kg of P ha^{-1} applied as rock phosphate, and 44 kg of P ha^{-1} as triple superphosphate). The subplots received two different types of residue management after legumes harvest: the legumes were harvested and the plant material left on the soil, or the plant parts were removed from the plots to simulate situations where the legume was harvested periodically as a fodder crop. According to the type of plant growth, siratro and tropical kudzu are prostrate, with a tendency to climb, while forage groundnut is a creeper plant.

The legumes were planted in February of 1995. Groundnut established poorly and had to be replanted at 75 days after trial installation. The speed at which the soil was covered was evaluated by a photographic method, using the software SIARCS[18].

Calopo, siratro and tropical kudzu were harvested at 5 and 9 months after planting. As forage groundnut was replanted in the dry season, it grew slowly, being cut for the first time at 7 months after trial installation. Calopo had problems after the first harvest, due to mite attack. The remaining species continued to be cut at 12, 21, 24, 35 and 38 months after trial installation. In all, six cuts of groundnut and seven cuts of siratro and tropical kudzu were made.

At each cut, shoot samples were collected to determine dry matter production and N, P and K contents. These samples were oven dried at 65°C until they showed constant weight. For N analysis the procedure of Bremner and Mulvaney[19] was followed, while P and K were determined after nitric-perchloric digestion[20]. P was analyzed colorimetrically, and K by flame photometry[17].

At 24 months after planting, at the end of the rainy season, shoot samples of the legumes that received triple superphosphate were also collected, with the aim of evaluating biological nitrogen fixation (BNF) by the ^{15}N natural abundance method[21]. At the same time, microplots (2.0 × 1.0 m) were demarcated in the subplots fertilized with triple superphosphate, and plant residues were removed. These microplots received 10 kg of N ha^{-1} as ammonium sulfate with 10 atom % ^{15}N, to evaluate BNF by the ^{15}N isotope dilution method[22]. As non-fixing control plants, the grasses *Panicum maximum* Jacq. ecotype KK 16 and *Brachiaria arrecta* (Hack ex T. Durand & Schinz) Stent were used. Legume and grass shoot samples were collected 35 months after planting, at the end of the dry season. The shoot samples were oven dried at 65°C, weighed and analyzed for total N and ^{15}N by mass spectrometry.

Soil samples were collected at 16 and 30 months after planting, from depths of 0–5, 5–10 and 10–20 cm, to evaluate the effect of cover crops on the following soil fertility parameters[17]: pH in water, exchangeable Al, exchangeable Ca, exchangeable Mg, available P, and exchangeable K.

Data for all variables were subjected to ANOVA procedures. Where significant differences were detected, Tukey's test was applied, at 0.05 probability level, to separate means.

Table 1. Percentage of soil covered by perennial herbaceous legumes in different periods of time.[1]

Legumes	Planting date	Percentage of soil covered at different times after trial installation							
		39 days	67 days	106 days	135 days	168 days	198 days	230 days	264 days
		(%)							
Forage groundnut	May 1995	NE[2]	NE	3	9	19	52	89	97
Calopo	February 1995	16ab	80a	93b	100a	100a	100a	100a	100a
Siratro	February 1995	22a	81a	94ab	100a	100a	100a	100a	100a
Tropical kudzu	February 1995	11c	52b	97a	100a	100a	100a	100a	100a

[1] Values in the same column followed by different letters indicate significant differences ($P \leq 0.05$) according to Tukey's test.
[2] NE, not evaluated.

Table 2. Dry matter production by perennial herbaceous legumes under two types of residue management over a period of 4 years.[1]

Legumes	Dry matter production	
	Residues left on the cultivated area	Residues removed from the cultivated area
	(Mg ha^{-1})	
1st year		
Calopo	5.6Ca	5.6Ca
Forage groundnut	13.1Ba	12.6Ba
Siratro	12.3Ba	12.7Ba
Tropical kudzu	15.2Aa	15.3Aa
2nd year		
Forage groundnut	15.0Aa	11.7Ab
Siratro	6.1Ca	6.2Ca
Tropical kudzu	9.4Ba	8.3Ba
3rd year		
Forage groundnut	5.5Aa	4.1Ab
Siratro	3.7Ba	3.5ABa
Tropical kudzu	3.4Ba	2.8Ba
4th year		
Forage groundnut	6.0Aa	4.0Ab
Siratro	4.0Ba	4.0Aa
Tropical kudzu	4.0Ba	3.4Aa

[1] Values followed by different capital letters (in the same column) or by small letters (in the same line), for each year, indicate significant differences ($P \leq 0.05$) according to Tukey's test.

Results and Discussion

Periods of time necessary for complete soil cover by the legumes varied from 135 days after planting of calopo, tropical kudzu and siratro, to 200 days after the replanting of forage groundnut (Table 1). Although after the first 135 days the first three legumes completely covered the soil surface, calopo and siratro covered the soil earlier, and at 67 days after planting showed 27 and 29% greater cover, respectively, than tropical kudzu. Groundnut was not compared to other legumes because it was replanted during the dry season, showing slower growth. Planting time influences soil cover velocity of groundnut. According to Espindola et al.[23], planting delayed from March to May, in the southeast of Brazil, caused an increase in the time necessary for complete soil cover from 130 to 190 days.

The periods of time for complete soil cover by the evaluated legumes were considerably larger than those values described for the annual legume velvet bean (*Mucuna pruriens*) on the same soil and climate conditions[23], emphasizing the importance of controlling weeds during the first months after planting for the perennial legumes.

Higher values were observed for dry matter production (Table 2) and accumulation of N, P and K (Table 3) in tropical kudzu during the first year compared to the other legumes. Forage groundnut overtook other legumes in dry matter production and accumulation of N during the following years. Considering the results during the first year, tropical kudzu produced up to 72% more dry matter than the other legumes, and it was superior to other species by up to 115, 88 and 262% for accumulation of N, P and K, respectively. The results described above were probably influenced by the fact that groundnut was replanted at 75 days after trial installation, having less time to produce dry matter and accumulate nutrients than the other species during the first year.

It is important to point out that high values observed in the first year for dry matter production and nutrients accumulation, compared to the second year, are related to the greater number of cuts made during that period (three in the first year against two in each of the next years).

From the second year onwards, prejudicial effects of removing plant residues were detected on dry matter production (Table 2) and nutrient accumulation (Table 3). There were different results between the evaluated legumes, with only forage groundnut being affected by residue management. Considering nutrient recycling, the two types of residue management have different effects on the sustainability of agroecosystems, with removal after the cut contributing to a higher exportation of nutrients. Natural leaf fall was observed in tropical kudzu and siratro in both the harvested and unharvested plots, which would reduce the effect of residue removal on soil nutrient supply. Consequently, residue removal of forage groundnut for agricultural practices such as hay production would only be viable if limiting soil nutrients are replaced by fertilization.

Table 3. Nitrogen, phosphorus and potassium accumulation by perennial herbaceous legumes under two types of residue management over a period of 4 years.[1]

Legumes	N accumulation		P accumulation		K accumulation	
	Retained[2]	Removed[3]	Retained[2]	Removed[3]	Retained[2]	Removed[3]
	(kg ha^{-1})					
1st year						
Calopo	139.7Ca	139.7Ca	11.4Da	11.4Da	45.0Da	45.0Da
Forage groundnut	354.9Ba	341.4Ba	22.5Ca	21.9Ca	93.7Ca	87.4Ca
Siratro	358.7Ba	349.4Ba	26.7Ba	26.7Ba	141.6Ba	128.4Ba
Tropical kudzu	438.9Aa	421.4Aa	32.8Aa	30.6Aa	208.1Aa	170.9Aa
2nd year						
Forage groundnut	406.0Aa	320.0Ab	27.1Aa	20.0Ab	92.2Aa	63.7Ab
Siratro	187.0Ca	178.6Ba	12.2Ba	11.9Ba	57.2Ba	58.5Aa
Tropical kudzu	270.6Ba	233.1Ba	17.4Ba	16.1ABa	79.8ABa	66.2Aa
3rd year						
Forage groundnut	179.7Aa	129.8Ab	10.4Aa	7.3Ab	42.3Aa	23.5Ab
Siratro	109.6Ba	102.9Ba	6.0Ba	5.6Aa	32.3Aa	28.6Aa
Tropical kudzu	98.2Ba	77.9Ca	5.9Ba	4.8Aa	25.6Aa	18.9Aa
4th year						
Forage groundnut	181.5Aa	123.5Ab	12.9Aa	10.4Ab	52.8Aa	23.5Ab
Siratro	121.5Ba	115.8Aa	9.0Ba	8.5ABb	52.7Aa	48.5Aa
Tropical kudzu	129.0Ba	102.7Aa	9.0Ba	7.2Bb	44.9Aa	30.8Aa

[1] Values followed by different capital letters (in a column) or by small letters (between ‘Retained’ and ‘Removed’ within each species), for each year, indicate significant differences ($P \leq 0.05$) according to Tukey’s test.
[2] Retained = residues left on the cultivated area.
[3] Removed = residues removed from the cultivated area.

Table 4. Delta ^{15}N values (δ^{15}N), proportion of N derived from biological nitrogen fixation (BNF; % Ndfa), and amounts of N fixed by perennial herbaceous legumes, estimated using the natural abundance of ^{15}N method with two different non-fixing control plants, at the end of the rainy season (24 months after planting). The legumes had been fertilized with phosphorus (44 kg ha^{-1} as triple superphosphate).[1]

Legumes/control plants	δ ^{15}N	% Ndfa		Amounts of N fixed	
		P. maximum	*B. arrecta*	*P. maximum*	*B. arrecta*
		(%)		(kg ha^{-1})	
Forage groundnut	0.40c	90.8a	88.6a	159.9a	158.0a
Siratro	1.69a	68.7c	59.8c	70.5a	61.9a
Tropical kudzu	0.88b	84.2b	78.5b	107.9a	100.2a
Control plants					
P. maximum	5.12	–	–	–	–
B. arrecta	4.18	–	–	–	–

[1] Values in the same column followed by different letters indicate significant differences ($P \leq 0.05$) according to Tukey’s test.

Considering all the cuts made of forage groundnut, tropical kudzu and siratro, it is significant to note their high potential for dry matter production and shoot accumulation of N and K. Forage groundnut produced 36 Mg of dry matter ha^{-1} and accumulated 1018 kg of N and 240 kg of K ha^{-1}, while tropical kudzu and siratro produced 31 and 26 Mg of dry matter ha^{-1}, respectively, and accumulated 886 and 762 kg of N ha^{-1}, and 323 and 274 kg of K ha^{-1}, respectively.

There were no significant differences between types of residue management for biological nitrogen fixation (BNF), evaluated using the ^{15}N natural abundance method obtained at the end of rainy season (Table 4). The results showed higher proportion (88.6–90.8%) of N fixed for forage groundnut, which was superior to other species by up to 28%. All the legumes presented high amounts of N fixed per hectare, varying from 62 to 160 kg of N ha^{-1}. Since P is supposed to increase N fixation, the obtained results should be observed with caution, because they were measured only in the plots fertilized with triple superphosphate, and therefore do not represent BNF of legumes without fertilization.

Table 5. Atom % ^{15}N atoms in excess, proportion of N derived from biological nitrogen fixation (BNF; % Ndfa) and amounts of N fixed by perennial herbaceous legumes estimated using the ^{15}N isotope dilution method, with *Brachiaria arrecta* as the non-fixing control plant, at the end of the dry season (35 months after planting). The legumes had been fertilized with phosphorus (44 kg ha^{-1} as triple superphosphate).[1]

Legumes/control plant	^{15}N atoms in excess	% Ndfa	Amounts of N fixed
	----------------------------(%)---------------------------		------- (kg ha^{-1}) ------
Forage groundnut	0.045a	67.5a	100.4a
Siratro	0.018a	86.8a	100.6a
Tropical kudzu	0.047a	66.6a	49.3a
Control plant			
B. arrecta	0.139	–	–

[1] Values in the same column followed by different letters indicate significant differences ($P \leq 0.05$) according to Tukey's test.

Table 6. Chemical properties [(a) pH, exchangeable Al, Ca + Mg; and (b) organic C, available P and K] of the soil covered by perennial herbaceous legumes, at three different depths (0–5, 5–10 and 10–20 cm).[1]

(a)

	Perennial herbaceous legumes								
	Forage groundnut			Siratro			Tropical kudzu		
Depth (cm)	pH	Al	Ca + Mg	pH	Al	Ca + Mg	pH	Al	Ca + Mg
		---- (cmol$^{(+)}$ dm^{-3}) ----			---- (cmol$^{(+)}$ dm^{-3}) ----			---- (cmol$^{(+)}$ dm^{-3}) ----	
0–5	4.5Ab	0.13Cb	4.2Ab	5.0Aa	0.01Bc	4.7Aa	4.5Ab	0.15Ba	4.1Ab
5–10	4.3Ba	0.20Aa	3.5Bb	4.5Ba	0.16Ab	3.9Ba	4.5Aa	0.16Ab	3.8Ba
10–20	4.5Aa	0.15Bb	3.5Ba	4.5Ba	0.16Aa	3.6Ca	4.5Aa	0.14Cc	3.6Bb

(b)

	Perennial herbaceous legumes								
	Forage groundnut			Siratro			Tropical kudzu		
Depth (cm)	Organic C	P	K	Organic C	P	K	Organic C	P	K
	(g kg^{-1})	-----(mg dm^{-3})----		(g kg^{-1})	-----(mg dm^{-3})----		(g kg^{-1})	-----(mg dm^{-3})----	
0–5	7.0Ab	5.8Aa	53.0Aa	7.7Aab	4.9Aa	57.0Aa	8.1Aa	5.6Aa	59.0Aa
5–10	6.9Bb	4.5Ba	28.0Ba	7.1Bab	4.1Ba	27.0Ba	7.2Ba	4.4Ba	40.0Ba
10–20	5.1Cb	4.0Ca	21.0Ba	5.3Cab	3.9Ca	25.0Ba	6.0Ca	3.9Ca	30.0Ba

[1] Values followed by different capital letters (in a column) or by small letters (between species for each soil parameter) indicate significant differences ($P \leq 0.05$) according to Tukey's test.

Using the enriched ^{15}N isotope dilution method, at the end of dry season, there were no significant differences between legumes for proportions or amounts of N fixed per hectare when *Brachiaria arrecta* was used as the non-fixing control (Table 5). Negative results were obtained with the use of *Panicum maximum* ecotype KK 16, suggesting that this species is not a good reference plant for use with the legumes evaluated by the ^{15}N isotope dilution method (data not shown). This may be related to differences in rooting patterns or in N uptake between the nitrogen-fixing plant and the non-fixing reference plant[24]. Comparing the ^{15}N natural abundance method with the ^{15}N isotope dilution method, Giller and Wilson[24] observed that, as the variation in δ^{15}N of available soil N with depth is usually small, the closeness with which the rooting patterns of the legumes and non-fixing controls need to be matched is not as critical in the ^{15}N natural abundance method as when using ^{15}N isotope dilution.

The results presented for nitrogen fixation in the plots where P was added to the soil are consistent with other reports[7,24], indicating the potential of the legumes evaluated in this study for adding large amounts of nitrogen to agroecosystems. However, some agricultural practices may affect the benefits of BNF. Successive cuts of perennial herbaceous legumes followed by removing plant residues temporarily reduce nitrogen fixation, due to the competition for carbohydrates between plant regrowth and nodule maintenance[25]. On the other hand, intercropping with non-legume plants reduces the prejudicial effects of cutting perennial legumes on nitrogen fixation, since those species act as a sink of N fixed[24].

The different levels of phosphate fertilization did not increase dry matter production of any legume (data not shown), demonstrating that the evaluated species are adapted to soils with low P fertility. Forage groundnut is indicated in the literature as a species capable of exploiting available P of the soil, even at high aluminum contents[26]. The tolerance of herbaceous legumes to soils with low available P is related to processes such as symbiosis with arbuscular mycorrhizal fungi[27] and secretion of phytase from plant roots[28], among other mechanisms.

Soil fertility evaluation, 16 months after planting, revealed significant interactions between legumes and soil depths for pH values, and exchangeable Al and Ca+Mg contents (Table 6a). Siratro presented higher pH values and Ca+Mg contents, associated with lower Al contents, in the 0–5 cm layer, when compared to forage groundnut and tropical kudzu.

Tropical kudzu promoted an accumulation of organic C in the soil statistically higher to forage groundnut at all the evaluated layers (Table 6b). A similar effect of tropical kudzu on soil organic matter has been reported[29], corroborating the benefit of this species to soil fertility.

Regarding plant residue management, an increase of exchangeable Ca+Mg and K contents was observed in the surface layer of the soil (0–5 cm) in the subplots where residues were cut and left on soil surface, contrasting with subplots where residues were cut and removed (data not shown). Consequently, residue management may also affect soil fertility, improving soil nutrient contents in the areas where residues are left on soil surface.

Results related to the second soil fertility evaluation, made at 30 months after planting, were similar to those formerly presented, and the data are not shown here.

Further understanding of the interactions between the evaluated perennial herbaceous legumes and fruit trees, involving aspects such as yield, mineral nutrition, pests, tolerance to shade and plant management, is required to ensure that appropriate cover crops are recommended for use in orchards.

Conclusions

Calopo, tropical kudzu and siratro covered the soil surface faster than other legumes, indicating that these species may contribute to protect soil against erosion and reduce the necessity of controlling weeds after planting.

Forage groundnut, tropical kudzu and siratro demonstrated high potential for dry matter production and shoot accumulation of N and K, being superior in this respect when compared to calopo, which suffered from mite attack. Such problems may limit the use of this cover crop in orchards.

In relation to biological nitrogen fixation, special attention should be given to forage groundnut, which showed a higher proportion of N fixed at the end of the rainy season, with P application. This characteristic allows reduced nitrogen fertilizer use in orchards. Different levels of phosphate fertilization did not increase dry matter production for any legume, indicating that the evaluated species are adapted to soils of low fertility. Besides, legume cultivation had an impact on soil chemical properties. Siratro increased soil pH and Ca+Mg contents, and reduced Al contents in the surface layer of the soil (0–5 cm) when compared to groundnut and tropical kudzu. Tropical kudzu promoted higher soil organic C contents when compared to groundnut. The results obtained suggest that both legumes improve soil fertility in orchard production systems.

According to this study, the use of forage groundnut, tropical kudzu and siratro as cover crops, with residues retained in the cultivated area, is an agronomic practice that furnishes high quantities of organic material and nitrogen to the soil and contributes towards sustainability in orchards.

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