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Selection of green manures to provide ecosystem services in a semi-arid environment

Seleção de adubos verdes para a prestação de serviços ecossistêmicos em ambiente semiárido

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ABSTRACT

Green manure is a soil management technique which provides several benefits to agroecosystems, improving the chemical, physical and biological quality of the soil, allowing them to provide different ecosystem services. Thus, the purpose of this work was to select green manures to compose multifunctional agroecosystems that provide ecosystem services in a semi-arid environment through the addition of biomass, C and N, and nutrient cycling. Thus, 29 treatments were evaluated in two cultivation cycles, using 14 species of legumes, oilseeds and grasses, distributed in single and intercropped crops. The green manures were cut at 70 days after sowing, and samples of the shoot and root parts were collected, with the production of fresh and dry biomass and the N, P, K, Ca, Mg and S levels being evaluated. C and biomass from rhizodeposition were also estimated. From these data, the accumulation of nutrients in the shoot and root biomass was calculated. Data were compared using descriptive and multivariate statistics. There is a positive relationship between the growing number of species used in consortium and the greater production of shoot and root biomass, favoring the increase in the capacity of the agroecosystem to provide provision and regulation services, with the latter being associated with climate change mitigation measures, highlighting the importance of biodiversity.

Keywords: conservationist management; agroecosystems; ecological services.

RESUMO

A adubação verde é uma técnica de manejo do solo que proporciona diversos benefícios aos agroecossistemas, melhorando a qualidade química, física e biológica do solo e permitindo que eles forneçam diferentes serviços ecossistêmicos. Assim, o objetivo do trabalho foi selecionar adubos verdes para compor agroecossistemas multifuncionais que prestem serviços ecossistêmicos em ambiente semiárido, por meio da adição de biomassa, C e N e da ciclagem de nutrientes. Para isso, foram avaliados, em dois ciclos de cultivo, 29 tratamentos utilizando-se 14 espécies de leguminosas, oleaginosas e gramíneas, distribuídas em cultivos solteiros e consorciados. Setenta dias após a semeadura, os adubos verdes foram cortados e coletaram-se amostras das partes aérea e radicular, nas quais foram avaliadas a produção de biomassa fresca e seca e os teores de N, P, K, Ca, Mg e S. Os teores de C e a biomassa proveniente de rizodeposição foram estimados. Com esses dados, foram calculados os acúmulos dos nutrientes na biomassa aérea e radicular. Os dados foram comparados por meio de estatística descritiva e multivariada. Existe uma relação positiva entre o número crescente de espécies utilizadas em consórcio e a maior produção de biomassa aérea e radicular, favorecendo o aumento da capacidade do agroecossistema na prestação de serviços de provisão e de regulação, este último associado às medidas de mitigação das mudanças climáticas, o que evidencia a importância da biodiversidade.

Palavras-chave: manejo conservacionista; agroecossistemas; serviços ecológicos.

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Introduction

Ecosystem Services are benefits from nature which have directly and indirectly been exploited by man for our own well-being (Boyd and Banzhaf, 2007). The historical process of land use and occupation was and still is marked by extractive exploitation of natural resources, with emphasis on agricultural activities (Montalvao, 2021). The continuous exploitation of resources in the form of natural capital tends to affect the provision of ecosystem services, which is evidenced by changes in the quality and quantity of available natural resources. The replacement of native vegetation by the introduction of agricultural production systems presents itself as one of the main forms of change in land use. In turn, these changes tend to increase the rate of soil organic matter (SOM) decomposition, partially contributing to a reduction in the quality of the physical, chemical and biological properties of the soil, which negatively influences the ecosystem services utilized by man (Caride et al., 2012; Costa et al., 2013). This allows us to affirm that soil degradation, whether resulting from changes in land use or inadequate management of agricultural crops, has compromised the provision of ecosystem services (Ferraz et al., 2019; Chaves et al., 2021). In this context, implementing environmental technologies in the form of low-cost actions that provide benefits to humans and directly or indirectly promote the recovery of ecosystem functions is of fundamental importance, being presented as functional alternatives for environmental sustainability. Among such actions and technologies available, the use of green manures, cultivated in consortium or in succession, has been a management strategy used in different agricultural crops which contributes to nutrient cycling and the establishment of new agroecosystems (Brandão, 2016; Lerner and Ferreira, 2016). Such strategies can bring benefits to commercial crops, being of great importance for the balance of agroecosystems, as it contributes to improve and maintain chemical, physical and biological aspects of the soil (Freitas, 2018). These technologies can help provide important ecosystem services through the soil, such as provision (food supply, water supply or addition of organic matter to the soil); regulation (erosion control, climate regulation); support (soil formation, nutrient cycling); and/or even cultural (ecotourism and education with ecological training). When integrated into production systems, green manures promote nutrient cycling, biological nitrogen fixation (BNF) and carbon (C) sequestration, among other benefits promoted by the input of shoot and root biomass of plants, including contributing to rhizodeposition (Giongo et al., 2016b; Giongo et al., 2020).

Green manure can be promoted through cultivating single species or in different mixtures of plant species, with leguminous and grass species being the most used (Giongo et al., 2021). In addition, green manures can be sown directly in consortium with commercial production, or in succession. Regardless of the system adopted, it is necessary to know the crop cycle and its edaphoclimatic requirements and interactions so that it is possible to guarantee good biomass production and nutrient cycling, aiming at greater efficiency in the provision of ecosystem services. In this sense, the purpose of this work was to select green manures to compose multifunctional agroecosystems that provide ecosystem services in a semi-arid environment through the addition of biomass, C and N, and the cycling of nutrients.

Material and Methods

The experiment was carried out in the Experimental Field of Bebedouro of the Brazilian Agricultural Research Corporation — Embrapa Semi-Arid Region (9º08'S, 40º18'W, 365.5 m altitude). The soil of the area is classified as Plintosolic Eutrophic Yellow Argissol (Cunha et al., 2010). The climate classification of the region is BSwh' according to the Köppen classification system, with annual average temperatures between 27 and 28°C during the first cycle and 25.5 and 6.5°C during the second experimentation cycle, according to data from EMBRAPA Semi-arid meteorological station.

A total of 14 plant species were selected, being 8 legumes, 3 grasses and 3 oilseeds. The legumes were: Calopogonium (*Calopogonium mucunoide* Desv.), Black velvet bean (*Stizolobium aterrimum* Piper & Tracy), Gray velvet bean (*Mucuna cochinchinensis* (Lour.) A.Chev.), Jack bean (*Canavalia ensiformis* L.), Rattlebox (*Crotalaria spectabilis* Roth), Sunn hemp (*Crotalaria juncea* L.), Lablab bean (*Dolichos lablab* L.), and Pigeon pea (*Cajanus cajan* (L.). The grass species were: Pearl millet (*Pennisetum americanum* L.), Corn (*Zea mays* L.), and Sorghum (*Sorghum vulgare* Pers.). The oilseed species were: Sunflower (*Helianthus annuus* L.), Castor bean (*Ricinus communis* L.) and Sesame (*Sesamum indicum* L.). The treatments consisted of monocultures and in different groups (Table 1).

According to the established levels of complexity, the species were grouped according to the characteristics of grasses (GRA), legumes (LEG) and oilseeds (OS). Thus, combinations were made to analyze the behavior of these species in groups.

The experimental design was randomized blocks with three replications, with 29 treatments (Table 1). Each experimental plot consisted of 4 m² and 5 planting rows, while each block (replication) was 20 m long × 6 m wide, with 3 m spacing between blocks (Figure 1).

The amount of seeds in intercropped crops was determined according to the recommendations made by Finney and Kaye (2017), and expressed in number of seeds per linear meter (Table 2) and weight of seeds per species (Table 3), adapting them to the climatic conditions prevailing in the region, also considering the experience and knowledge of specialists and local producers in the respective treatments.

The seeds were weighed and distributed in plastic bags identified with the respective treatments and planting lines, considering the information contained in Tables 2 and 3. Two cultivation cycles were carried out, with the first cycle in March 2019 and the second in March 2020.

Table 1 – Distribution of green manure species by treatment.

Treatment	Composition
T1-Legume – LEG	Calopogonium - CAL
T2-Legume – LEG	Gray velvet bean - GVB
T3-Legume – LEG	Black velvet bean - BVB
T4-Legume – LEG	Jack bean - JB
T5-Legume – LEG	Rattlebox – RAT
T6-Legume – LEG	Sunn hemp - SUH
T7-Legume – LEG	Lablab bean - LAB
T8-Legume – LEG	Pigeon pea - PIP
T9-Grass – GRA	Pearl Millet - PM
T10-Grass - GRA	Corn - CN
T11-Grass – GRA	Sorghum - SOR
T12-Oilseed – OS	Castor bean - CB
T13-Oilseed – OS	Sesame - SES
T14 – 1 LEG + 1 GRA	JB + CN
T15 – 1 GRA + 1 OS	CN + CB
T16 – 1 LEG + 1 OS	JB + CB
T17 – 1 LEG + 1 GRA + 1 OS	JB + CN + CB
T18 – 2 LEG + 1 GRA + 1 OS	BVB + JB + SOR + SF
T19 – 2 LEG + 2 GRA + 1 OS	GVB + RAT + SOR + PM + CB
T20 – 1 LEG + 2 GRA + 2 OS	PIP + CN + SOR + SES + SF
T21 – 1 LEG + 1 GRA + 2 OS	LAB + CN + CB + SES
T22 – 2 LEG + 2 GRA + 2 OS	LAB + CAL + PM + SOR + CB + SF
T23 – 3 LEG + 2 OS	GVB + CAL + PIP + SF + SES
T24 – 3 LEG + 3 GRA + 3 OS	BVB + JB + LAB + CN + SOR + PM + CB + SF + SES
T25 – 4 LEG + 3 GRA +3 OS	CAL + BVB + JB + LAB + CN + SOR + PM + SF + CB + SES
T26 – 5 LEG + 3 GRA + 3 OS	CAL + BVB + JB + LAB + PIP + CN + PM + SOR + CB + SES + SF
T27 – 6 LEG + 3 GRA + 3 OS	CAL + BVB + RAT + JB + LAB + PIP + CN + SOR + PM + SF + CB + SES
T28 – 7 LEG + 3 GRA + 3 OS	CAL + BVB + RAT + SUH + JB + LAB + PIP + CN + SOR + PM + SF + CB + SES
T29 – 8 LEG + 3 GRA + 3 OS	CAL + GVB + BVB + RAT + SUH + JB + LAB + PIP + CN + SOR + PM + SF + CB + SES

CAL: Calopogonium; GVB: Gray velvet bean; BVB: Black velvet bean; JB: Jack bean; RAT: Rattlebox; SUH: Sunn hemp; LAB: Lablab bean; PIP: Pigeon pea; PM: Pearl millet; CN: Corn; SOR: Sorghum; SF: Sunflower; CB: Castor bean; SES: Sesame.

Sowing was performed manually, distributing the seeds in continuous shallow furrows. The crop was irrigated daily by a surface drip system with a flow of 4.0 L h^{-1}, using reference evapotranspiration (ETo) data.

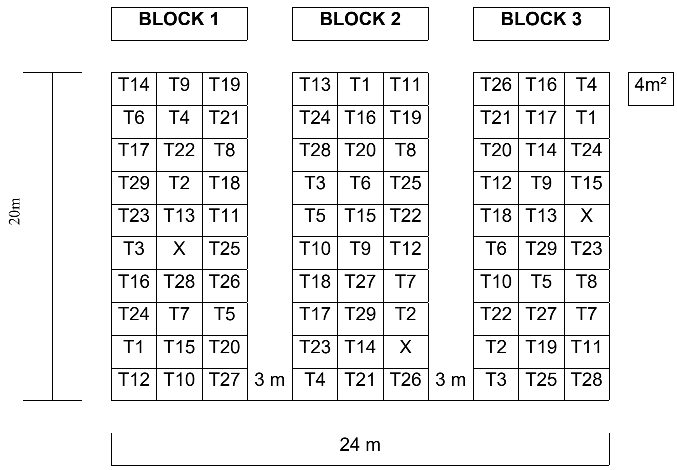

Figure 1 – Schematics of the distribution of treatments in the experiment.

After 70 days of planting, the shoot biomass of green manures (leaves, stems, flowers) was collected in a quadrant of 1 m² in the central region of each plot. The samples were weighed, cut and homogenized. Samples of the root system were also collected at depths of 0-20, 20-40 and 40-60 cm using a Soil collector tube, with a height of 20 cm and 5.1 cm in diameter. Next, three simple samples were collected in the planting row and three between the rows in each treatment by depth, which were homogenized to compose a composite sample. Still in the field, the samples were washed with running water using a sieve (mesh 8) to remove the soil, and soon after they were submitted to a second washing in the laboratory with distilled water, then dried with a paper towel. The plant tissue samples from both the shoot and the root system were weighed and placed in an oven with forced air circulation at a temperature of 65°C for 72 hours. The dry matter contents of the samples were calculated, and then the total production of dry phytomass per hectare was estimated from these calculations.

The rhizodeposition, considered as all material from the roots and not recovered by sampling, including exudates, was calculated according to Bolinder et al. (2007) using the coefficient 0.65 from the root biomass.

The DM samples from each treatment were ground in a Willey-type mill (sieve with a mesh size of 1 mm) to determine the nitrogen (N) contents by the Kjeldahl method; P by colorimetry; Ca and Mg by Flame atomic absorption spectrophotometry; K by flame photometry; and S by turbidimetry (Carmo et al., 2000), all after digestion of the samples by a wet method with nitric-perchloric (3:1). Carbon (C) was estimated based on guidelines from Bolinder et al. (2007). The accumulation of nutrients in the shoots and in the root system of the treatments was calculated from the dry phytomass production and the nutrient contents in the plant tissue.

The total biomass and the total accumulation of nutrients result from the sum of the values obtained from the shoot and root.

Table 2 – Number of seeds per species of green manure in each treatment.

TREAT	Number of seeds per linear meter													
	CAL	GVB	BVB	JB	RAT	SUH	LAB	PIP	PM	CN	SOR	SF	CB	SES
T1	52													
T2		21												
T3			21											
T4				21										
T5					52									
T6						52								
T7							52							
T8								26						
T9									52					
T10										26				
T11											52			
T12													26	
T13														52
T14				11						13				
T15										13			13	
T16				11									13	
T17				8						8			8	
T18			6	6							13	8		
T19		6			11				11		11		6	
T20								6		6	11	6		13
T21							13			8			8	13
T22	11						11		11		11	6	6	
T23	11	6						6				6		11
T24			3	3			8		8	6	8	6	6	8
T25	6		3	3			6		6	3	6	3	3	6
T26	6		3	3			6	3	6	3	6	3	3	6
T27	6		3	3	6		6	3	6	3	6	3	3	6
T28	6		3	3	6	6	6	3	6	3	6	3	3	6
T29	6	3	3	3	6	6	6	3	6	3	6	3	3	6
TOTAL	104	36	45	75	81	64	114	50	112	95	136	73	101	127

CAL: Calopogonium; GVB: Gray velvet bean; BVB: Black velvet bean; JB: Jack bean; RAT: Rattlebox; SUH: Sunn hemp; LAB: Lablab bean; PIP: Pigeon pea; PM: Pearl millet; CN: Corn; SOR: Sorghum; SF: Sunflower; CB: Castor bean; SES: Sesame; TREAT: Treatment.

The data were submitted to Pearson's linear correlation analysis ($p < 0.05$) and the means were presented in graphs along with the standard deviation. Multivariate statistical techniques were used, such as Factor Analysis (FA) and Cluster Analysis (CA). Only variables with significant factor loadings in FA were used in the CA. Moreover, the Euclidean distance was used as a measure of similarity between the records and the Ward's method as a grouping strategy in the CA, tracing a horizontal Fenon Line to determine the number of groups formed, and then observing whether there were any composition patterns or not. The groups formed by the CA were compared by means of multivariate analysis of variance using the F test.

Table 3 – Seed weight by green manure species.

SPECIES	Weight of 100 seeds (g)	Weight of one seed (g)
SUNN HEMP	4.50	0.045
RATTLEBOX	1.71	0.0171
CALOPOGONIUM	1.28	0.0128
JACK BEAN	187.00	1.87
SESAME	1.00	0.01
SUNFLOWER	6.27	0.0627
PIGEON PEA	8.50	0.085
LABLAB BEAN	20.00	0.2
CASTOR BEAN	69.08	0.6908
PEARL MILLET	1.00	0.01
CORN	30.00	0.3
GRAY VELVET BEAN	84.45	0.8445
BLACK VELVET BEAN	84.45	0.8445
SORGHUM	2.50	0.025

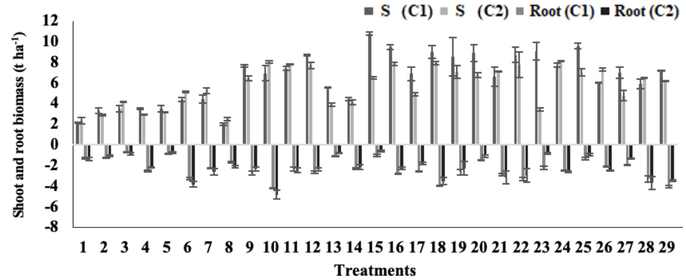

Figure 2 – Shoot and root dry biomass production of different green manures in single and intercropped crops.
S: Shoot; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

Results and Discussion

Production of shoot and root biomass, rhizodeposition and carbon

It is observed that the lowest shoot biomass productions were obtained when leguminous species in single cultivation (T1 to T8) were used as green manure (Figure 2), while grass species in single cultivation (T9 to T11) showed good production of shoot biomass, being similar to some of the intercropped treatments. Castor bean (T12) showed good shoot biomass production for the oilseed species, close to the grass group, while the sesame (T13) production was close to the values obtained by the legume group (Figure 2). Only 3 species of green manures were used in treatments T14 to T16, one from each functional group. It is observed that the use of castor bean (oilseed) in association with the jack bean (T15) and with the corn grass (T16) increased the shoot biomass production capacity of the intercropping when compared with the intercropping with jack bean and corn (T14), showing a beneficial effect on the composition. An ecosystem synergism can occur when a cropping system is formed by species with greater production potential, meaning that a coordinated effort of the different species which compose the system can result in greater biomass accumulation.

Treatments T17 to T29 are characterized by increased complexity related to the number of species and functional groups used (Table 1) in the consortia composition. In these treatments, there is generally a benefit to consortia in the shoot biomass production, and this synergistic effect of the addition of species is smaller in treatments with the maximum number of species used (T26 to T29). It is also important to highlight that the increase in plant diversity can also reduce the net primary production capacity of the species which need to compete for space and nutrients with the others (Almeida and Câmara, 2011) if there is no ecosystem synergism. For example, the shoot and root biomass production of T10 and T12 (corn and castor bean in single cultivation), which are fast growing species, was higher than T17 formed by plant mixtures (jack bean, corn and castor bean), in which both castor bean and corn are component species. However, an example of a synergistic effect is T18, which, despite being composed of only 4 species (2 legumes (black velvet bean and jack beans), 1 grass (sorghum) and 1 oilseed (sunflower)), showed both higher shoot and radicular biomass production when compared to treatments with a higher degree of complexity, such as T25 to T27 (Figure 2). This advantage of the association of species in the same agricultural system can be corroborated by the study by Pausch and Kuziakov (2018), who concluded that grasses have a greater allocation of C in the roots, especially the perennials, contributing to greater C inputs in the soil when compared to the grasses for other annual crops, being an important group to compose the consortia of green manures.

In some cases in the consortia with the largest number of species, the synergistic benefit in the increase of both the root and shoot biomass production is observed, with the development of more detailed studies on the contribution of each species being important, as well as the characterization of the root exudates and the microbial population present in the rhizosphere of these systems. In this case, just as shoot biomass presents benefits associated with the availability of OM, the root system, in turn, presents characteristics which enable improvements in the structural properties of the soil, in the cycling of nutrients, and in the reduction of erosive processes (Blanco-Canqui et al., 2015), as well as in the C input (Pausch and Kuziakov, 2018).

Out of all the treatments, T10, composed of corn in single cultivation, showed the highest rhizodeposition, with 2.72 t ha^{-1} in 2019 and 3.15 t ha^{-1} in 2020 (Figure 3). The difference in rhizodeposition in the treatments is directly related to the contribution of shoot or root biomass in the systems (Bolinder et al., 2007), and this biomass production is a determining factor of its nutritional requirement (Crusciol et al., 2013).

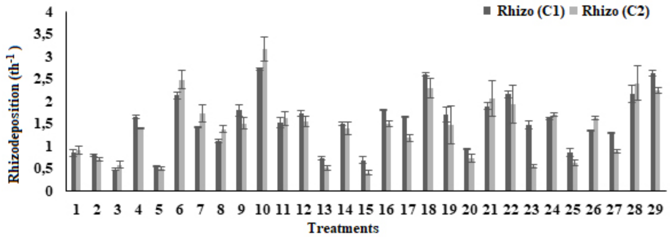

Figure 3 – Root rhizodeposition of different green manures in single and intercropped crops.
Rhizo: Rhizodeposition; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

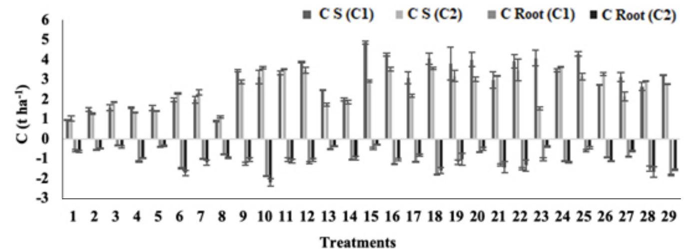

Figure 4 – Carbon accumulation of shoot and root biomass of different green manures in single and intercropped crops.
C: Carbon; S: Shoot; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

This characteristic consequently tends to boost the production and release of exudates to the soil, intensifying the beneficial relationships to the agroecosystem.

The rhizodeposition of green manures can contribute to increase the density of the microbial population in the soil, since they provide food for them. In addition, both fine roots, root hairs and compounds excreted through root activity tend to stimulate the degradation of harmful chemical compounds and have a binding effect on solid soil constituents, aggregating them (Rocha et al., 2004; Monquero et al., 2013; Villarino et al., 2021).

When the C accumulation between treatments is observed (Figure 4), considering that this is directly related to the contribution of shoot and root biomass (Bolinder et al., 2007), the same trend is observed, for leguminous species in single crops showed the lowest accumulations, while grasses (T9 to T11) and castor beans (T12) had similar performance to mixtures of green manures, with greater potential to add C to the soil. Even though T18 (BVB + JB + SOR + SF) used a smaller number of species among the treatments, it showed C accumulation in the shoot and root biomass in both crops, being 5.85 t ha^{-1} in 2019 and 5.15 t ha^{-1} in 2020, and being similar to more complex treatments, such as T22, T23, T25 and T29, for example. The Carbon, initially atmospheric, can accumulate in plant cells, which will later be incorporated into the soil through biomass, thereby altering the physical, chemical and biological properties of soils (Ribeiro et al., 2011). In this sense, agroecosystems, which include cultivated green manures, influence soil recovery processes with the addition of C (Blanco-Canqui et al., 2015), and their effectiveness is related to the species used (Bolinder et al., 2007).

Nitrogen accumulation

The mixture of green manures (T23) showed the highest accumulation of nitrogen in the shoot and root in the first cycle, with 136.37 kg ha^{-1} in 2019, followed by treatments T12 (castor beans) with 120.19 kg ha^{-1} in 2019 and 106.85 kg ha^{-1} in 2020, T15 with 117.81 kg ha^{-1} in 2019 and 70.61 kg ha^{-1} in 2020, and T16 with 110.60 kg ha^{-1} in 2019 and 91.43 kg ha^{-1} in 2020 (Figure 5).

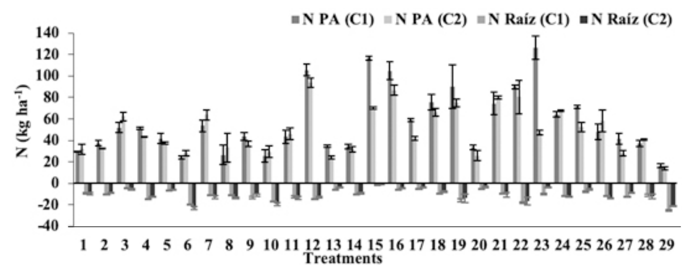

Figure 5 – Nitrogen accumulation of shoot and root biomass of different green manures in single and intercropped crops.
N: Nitrogen; S: Shoot; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

Among the single crops, castor bean (T12), an oilseed species with good capacity for extracting nutrients in deep layers (Savy Filho et al., 1999) and producing biomass (Favarato et al., 2017), stood out among other species, including legumes. Studies demonstrate the importance of the diversity and activity of free-living diazotrophs in the entry of N into soils cultivated with castor bean, being important for maintaining nitrogen stocks in the soil and microbial biomass over time (Mendes et al., 2015; Fracetto et al., 2019). In addition, this species showed similar or higher N accumulation capacity than treatments with a greater number of species, including in the root system. These characteristics demonstrate that the use of castor bean can be of great importance for the supply and cycling of N in agroecosystems.

Macronutrient accumulation

The highest accumulations of P occurred in the monocultures T11 (Sorghum), T12 (Castor beans) and T10 (Corn), followed by the treatments composed by the highest proportions of species: T29 with 14 species and T28 with 13 species. Sorghum and corn (De Miranda and De Miranda, 2011), as well as castor bean, were classified as highly mycorrhizal dependent species, and therefore are more efficient in the use of phosphorus. The use of these species in agroecosystems, whether in rotation or consortium, benefits other species in P accumulation.

Alves et al. (2002) also point out that the ability to acquire P from the environment and its efficient use are related to the morphological characteristics of the root system, which, as in the case of grasses, have a longer length, more volume, and thinner roots. These characteristics may justify the efficiency and accumulation of P in treatments with the presence of grasses.

The T29 and T28 treatments present many species in their composition, and therefore promoted a more intense incorporation of P. The use of green manures in simultaneous cultivation systems increases P cycling, thus reducing the need for P input by fertilizers for commercial cultivation (Daryanto et al., 2018). Maltais-Landry and Frossard (2015) add that the cultural residues of green manures can release P available to plants in the soil during the decomposition process of organic matter. In other words, the use of green manures in irrigated agroecosystems makes it possible to provide regulatory and support services to the system through the cycling of nutrients, including P (Figure 6).

The T15 (CN + CB), T19 (GVB + RAT + SOR + PM + CB) and T18 (BVB + JB + SOR + SF) treatments composed by cultures of green manure mixtures, in addition to the monoculture formed by pearl millet (T9), were more efficient in accumulating K in their tissues (Figure 7). It is important to point out that the high K accumulation capacity of leguminous species makes them an excellent alternative for use in multifunctional agroecosystems (Teodoro et al., 2011) in view of the purpose of incorporating K into the soil system.

The highest total Ca accumulations were observed in the castor bean monoculture (T12) with 210.25 kg ha^{-1} in 2019 and 187.01 kg ha^{-1} in 2020, followed by the intercropping of jack beans and castor beans (T16) with 189.09 kg ha^{-1} in 2019 and 109.86 kg ha^{-1} in 2020 (Figure 8). Once again, castor bean stood out in terms of its ability to accumulate a nutrient, indicating that it is a species with a high capacity for nutrient cycling. The calcium present in the biomass after the decomposition and mineralization process can contribute to the flocculation of clays, and consequently to forming a greater amount of soil aggregates and its stability (Sumner, 2009; Sena et al., 2020).

Treatments formed by more than one plant species showed the highest Mg accumulations in their tissues, such as T22 with 40.15 kg ha^{-1} in 2019 and 35.98 kg ha^{-1} in 2020, T15 with 39.11 kg ha^{-1} in 2019 and 23.44 kg ha^{-1} in 2020, and T18 with 36.03 kg ha^{-1} in 2019 and 31.54 kg ha^{-1} in 2020 (Figure 9). The cycling of nutrients such as potassium (K), calcium (Ca) and magnesium (Mg) present in the shoot and root biomass of green manures is an alternative for the recovery of soil fertility, especially when cultivated in mixtures between species of grasses, legumes and oilseeds (Brandão, 2016; Giongo et al., 2016a).

Sulfur accumulation was higher in the T12 treatment (CB) with 45.59 kg ha^{-1} in 2019 and 40.51 kg ha^{-1} in 2020, T16 (JB + CB) with 38.84 kg ha^{-1} in 2019 and 32.14 kg ha^{-1} in 2020, and T23 (GVB + CAL + PIP + SF + SES) with 37.30 kg ha^{-1} in 2019 and 14.00 kg ha^{-1} in 2020.

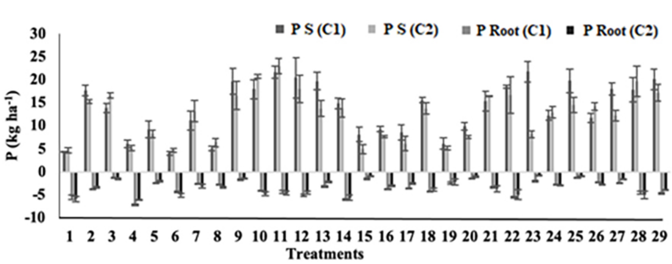

Figure 6 – Phosphorus accumulation in shoot and root biomass of different green manures in single and intercropped crops.
P: Phosphorus; S: Shoot; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

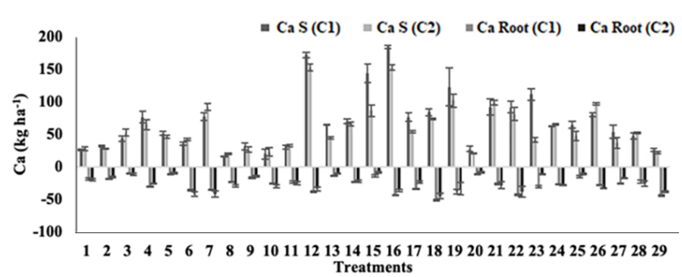

Figure 8 – Calcium accumulation in shoot and root biomass of different green manures in single and intercropped crops.
Ca: Calcium; S: Shoot; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

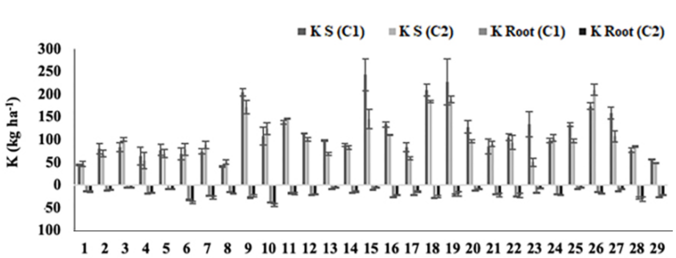

Figure 7 – Potassium accumulation in shoot and root biomass of different green manures in single and intercropped crops.
K: Potassium; S: Shoot; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

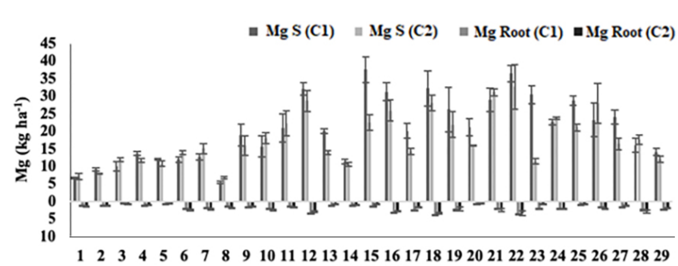

Figure 9 – Magnesium accumulation in shoot and root biomass of different green manures in single and intercropped crops.
Mg: Magnesium; S: Shoot; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

Treatments 12 and 16 once again were the greatest accumulators of nutrients, having the presence of an oilseed in common. T12, composed of castor bean, also had the highest S accumulation among all evaluated treatments (Figure 10).

On average, regardless of the crop cycle, the accumulation of macronutrients in the shoot followed the sequence: K > Ca > N > Mg > S > P, while in the root system it was: Ca > K > N > S > P > Mg.

The provision of ecosystem services can be favored by an abundance of characteristics promoted by the diversity of species, and independent of the high biomass production (Finney et al., 2016; Finney and Kaye, 2017), the different individual characteristics or when cultivated in a mixture, indicating that there are differences in the capacities of species to provide ecosystem services.

The factor loadings in the factor analysis (Table 4) tend to expose the existing relationship between variables and factors, enabling identification of the variables of greater importance or weight (highlighted in bold). The variables with the greatest weight in Factor 1, which explains 45.29% of the data variability, are rhizodepositions, carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, boron, manganese and zinc accumulated in the root system biomass; in Factor 2, with 25.61% of data variability, the accumulation of carbon, nitrogen, calcium, magnesium, sulfur, copper, iron, manganese and sodium are in the shoot biomass; in Factors 3 and 4, it was the accumulation of P and K in the shoot biomass, explaining 6.85 and 4.66% of data variability, respectively, corresponding to 82.41% of the total accumulated variance. Such indicators show that the greatest differences between green manure compositions result from their ability to accumulate nutrients, mainly in the root system and rhizodeposition (45.29%). Thus, the input capacity of C and nutrients in deeper soil layers is the main differential of the evaluated treatments.

It is important to emphasize that, despite the differences between them, other factors must be taken into account when implementing an agroecosystem which uses green manures efficiently, in addition to the benefits arising from the species or mixtures of species and the objectives to be achieved by the producer, such as the availability of technical, economic and material resources needed to implement this type of technology.

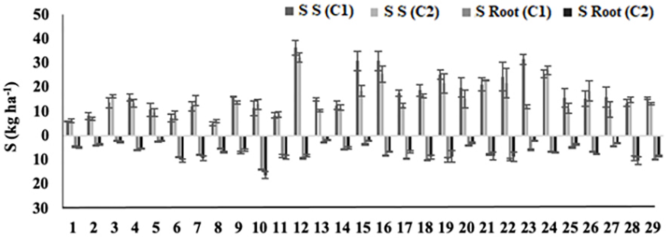

Figure 10 – Sulfur accumulation in shoot and root biomass of different green manures in single and intercropped crops.
S: Sulfur; S: Shoot; C1: Cycle 1 (2019); C2: Cycle 2 (2020).

The availability of nutrients in the system is associated with the ability of green manures to cycle nutrients from deep soil layers (Leijster et al., 2019), leaving them available in the surface layers after the decomposition processes of shoot and root biomass, thus favoring the provision of ecosystem services. The carbon present in the shoot is one of the most important services of green manures, as it guarantees a greater return of organic matter to the soil, and improvements in soil quality (Garcia-Franco et al., 2015), as evidenced in its physical structure.

Table 4 – Factor loadings in the different variables observed.

Variables	Two Cycles (2019 and 2020)			
	Factor 1	Factor 2	Factor 3	Factor 4
RO:S rati	0.64	-0.44	-0.33	-0.43
Rhizo	**0.98**	0.10	0.10	0.03
C S	0.28	**0.71**	0.32	0.50
N S	-0.05	**0.94**	-0.04	0.02
P S	0.21	0.14	**0.87**	0.08
K S	0.06	0.49	-0.05	**0.72**
Ca S	0.01	**0.92**	-0.17	-0.12
Mg S	0.18	**0.86**	0.20	0.32
S S	0.06	**0.91**	0.07	0.12
B S	0.19	0.56	0.49	-0.29
Cu S	0.16	**0.71**	0.27	0.44
Fe S	0.13	**0.82**	0.11	0.16
Mn S	0.09	**0.85**	0.31	0.11
Zn S	0.30	0.64	0.32	0.54
Na S	0.21	**0.77**	-0.07	0.49
C RO	**0.98**	0.10	0.10	0.03
N RO	**0.80**	-0.15	0.02	-0.10
P RO	0.59	-0.03	-0.01	-0.63
K RO	**0.93**	0.05	-0.02	-0.02
Ca RO	**0.79**	0.43	-0.22	-0.16
Mg RO	**0.74**	0.58	-0.02	-0.06
S RO	**0.94**	0.13	0.08	0.04
B RO	**0.77**	-0.02	0.34	0.09
Cu RO	0.54	0.32	0.28	0.16
Fe RO	**0.70**	-0.01	0.33	0.14
Mn RO	**0.86**	0.27	0.12	0.15
Zn RO	**0.89**	0.33	0.10	-0.02
Eigenvalues	12.23	6.92	1.85	1.26
Total variance (%)	45.29	25.61	6.85	4.66
Accumulated variance (%)	45.29	70.90	77.75	82.41

S: Shoot; Rati: Ratio; RO: Root; Rhizo: Rhizodeposition; C: Carbon; N: Nitrogen; P: Phosphorus; K: Potassium; Ca: Calcium; Mg: Magnesium; S: Sulfur; B: Boron; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc; Na: Sodium.

The N accumulation in both the shoot (Factor 2) and in the root system (Factor 1) is an extremely necessary ecosystem service, once that it directly acts on the net primary production of crops, enabling higher yields in agricultural crops (Couëdel et al., 2018). The allocation of resources by the plant and the return in biomass and nutrients through the decomposition of the roots are very important to guarantee the provision of ecosystem services (Daryanto et al., 2018).

Next, a cluster analysis was performed based on the results obtained in the FA in order to identify groups with similar capabilities to provide ecosystem services, excluding the less important variables and grouping all the others with factor loading > 0.7 present in the two first factors, and grouping the treatments into five groups (G1, G2, G3, G4 and G5) (Figure 11). The formation of these groups made it possible to identify that it is feasible to differentiate the different treatments based on the individual or collective benefits evidenced in the accumulation of biomass, C, N, rhizodeposition and other macronutrients.

Table 5 shows the treatments that make up each of the groups, while Table 6 shows the averages of the variables for each of the groups, as well as the comparison between the groups through multivariate analysis of variance.

The formation of groups between treatments occurred due to the similarities of some variables evaluated. In this sense, a multivariate analysis of variance was performed in order to verify whether there are significant differences between the groups formed, with the F test to compare the groups (Table 6). All groups were statistically different and can be used depending on the characteristics presented, such as the capacity to supply biomass, C and nutrients, both by the shoot and by the root system, the needs of the producer and the availability and adaptation of the species in the region. In the comparison of the different groups formed, it was observed that the biomass and C variables presented higher average indices, in addition to being great influencers of the formations of the groups, and they still tend to have a strong influence on the physical and chemical properties of the soil (Zornoza et al., 2015).

The G1 group was mostly formed by treatments with green manures cultivated in consortium, but in consortia with a smaller number of species, where the presence of at least one oilseed within the treatments was observed, namely the two cycles of treatments T12, T16, T18, T21, and T22, in addition to cycle 1 of T15 and T23 (Figure 11), which joined the group due to variables with similar weight for shoot biomass. This group showed greater capacity to accumulate N, C, Ca, Mg, S, Cu, Fe, Mn and Na from the shoot, in addition to Ca and Mg in the root system (Table 6). This group is very important when the purpose is to produce shoot biomass for the production of litter for ground cover, and for the regulation service by the fixation of C and N in the shoot biomass. Furthermore, it allows the release of nutrients in the most superficial layer of the soil.

The G2 group was formed by corn and pearl millet grasses in single cultivation, and in consortium of green manures with a greater number of species in the presence of the three species of grasses, except for T19 with two. The main characteristic in the group is potassium accumulation in the shoot, making it an excellent alternative when the objective is to improve the availability of this nutrient in production systems, also benefiting the physical conditions of the soil as this element allows for a decrease in clay dispersion and improvements in soil aggregation and stability (Phocharoen et al., 2018).

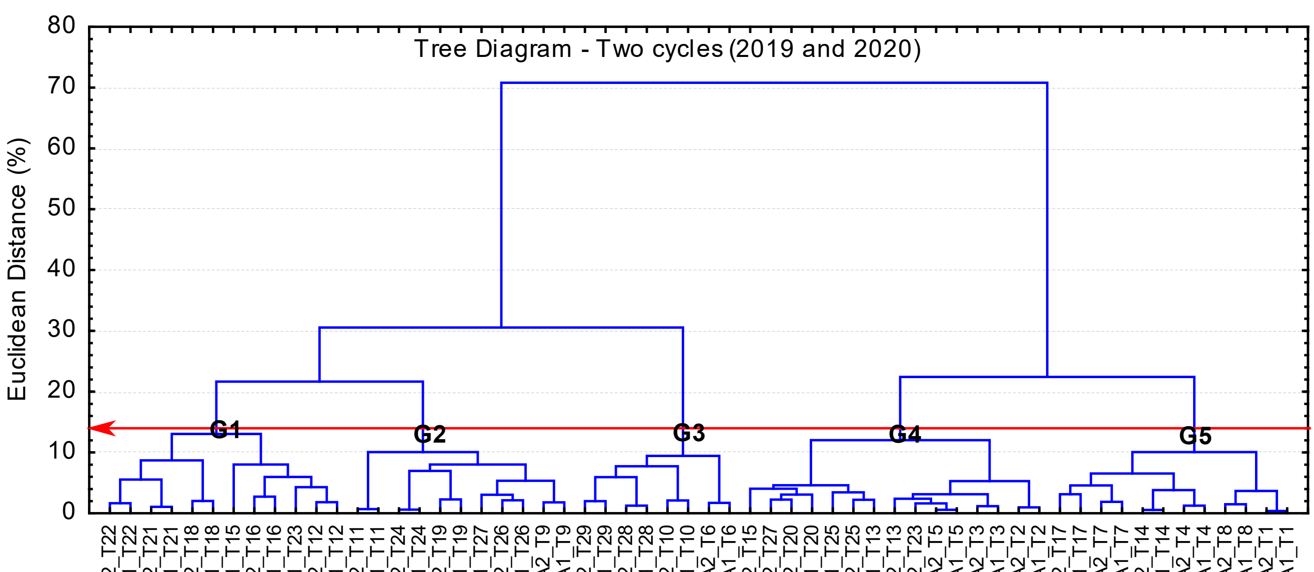

Figure 11 – Grouping referring to variables with load > 0.7 of the 29 treatments of green manures cultivated in the Brazilian semi-arid region.
A1: Cycle 1 (2019); A2: Cycle 2 (2020); T: Treatment; G1: Group 1; G2: Group 2; G3: Group 3; G4: Group 4; G5: Group 5.

Table 5 – Composition of groups by treatments and species.

Groups	Treatments/Cycle	Composition of species by treatment
G1	T12C1, T12C2, T15C1, T16C1, T16C2, T18C1, T18A2, T21C1, T21C2, T22C1, T22C2, T23C1	T12 – Castor bean - CB T15 - CN + CB T16 - JB + CB T18 - BVB + JB + SOR + SF T21 - LAB + CN + CB + SES T22 - LAB + CAL + PM + SOR + CB + SF T23 - GVB + CAL + PIP + SF + SES
G2	T9C1, T9C2, T11C1, T11C2, T19C1, T19C2, T24C2, T24C2, T26C1, T26C2, T27C2	T9 – Pearl millet - PM T11 – Sorghum - SOR T19 - GVB + RAT + SOR + PM + CB T24 - BVB + JB + LAB + CN + SOR + PM + CB + SF + SES T26 - CAL + BVB + JB + LAB + PIP + CN + PM + SOR + CB + SES + SF T27 - CAL + BVB + RAT + JB + LAB + PIP + CN + SOR + PM + SF + CB + SES
G3	T6C1, T6C2, T10C1, T10C2, T28C1, T28C2, T29C1, T29C2	T6 - Sunn hemp - SUH T10 – Corn - CN T28 - CAL + BVB + RAT + SUH + JB + LAB + PIP + CN + SOR + PM + SF + CB + SES T29 - CAL + GVB + BVB + RAT + SUH + JB + LAB + PIP + CN + SOR + PM + SF + CB + SES
G4	T2C1, T2C2, T3C1, T3C2, T5C1, T5C2, T13C1, T13C2, T15C2, T20C1, T20C2, T23C2, T25C1, T25C2, T27C2	T2 – Gray velvet bean - GVB T3 – Black velvet bean - BVB T5 - Rattlebox- RAT T13 – Sesame - SES T15 - CN + CB T20 - PIP + CN + SOR + SES + SF T23 - GVB + CAL + PIP + SF + SES T25 - CAL + BVB + JB + LAB + CN + SOR + PM + SF + CB + SES T27 - CAL + BVB + RAT + JB + LAB + PIP + CN + SOR + PM + SF + CB + SES
G5	T1C1, T1C2, T4C1, T4C2, T7C1, T7C2, T8C1, T8C2, T14C1, T14C2, T17C1, T17C2	T1 – Calopogonium - CAL T4 – Jack bean - JB T7 – Lablab bean- LAB T8 – Pigeon pea - PIP T14 - JB + CN T17 - JB + CN + CB

T: Treatment; C1: Cycle 1; C2: Cycle 2; G1: Group 1; G2: Group 2; G3: Group 3; G4: Group 4; G5: Group 5; CAL: Calopogonium; GVB: Gray velvet bean; BVB: Black velvet bean; JB: Jack bean; RAT: Rattlebox; SUH: Sunn hemp; LAB: Lablab bean; PIP: Pigeon pea; PM: Pearl millet; CN: Corn; SOR: Sorghum; SF: Sunflower; CB: Castor bean; SES: Sesame.

It is worth mentioning that, in addition to the greater potassium accumulation, this group was similar to G1 for most variables, except for N and Ca accumulation in the shoot, which was lower than in G1. It is an important group to be used in irrigated production areas, with high potassium input via fertilization, especially in sandy soils, allowing the recovery of this nutrient at greater depths, making it available in more superficial layers for root absorption of crops.

In turn, the T28 and T29 treatments with the highest number of intercropped species are grouped in G3, in addition to the single T6 (Sunn hemp) and T10 (Corn) treatments from both cycles. All treatments stood out in terms of root phytomass production, presenting the highest means of rhizodeposition and phosphorus accumulation in the shoot, and carbon, nitrogen, potassium, sulfur, boron and zinc accumulation in the root system (Table 6). This group becomes very important when the intention is to improve the quality of the soil in depth, promoting biological diversity and soil aggregation.

The G4 group is formed by T2, T3, T5, T13, T20 and T25 from the two cycles, and T15, T23 and T27 from cycle 2. The group has mostly leguminous species, with the exception of T13 and T15 treatments, which were united as a result of similar variables of C and rhizodeposition (Figures 3 and 4). On the other hand, G5 is composed of treatments with single legume cultivation (T1, T4, T7 and T8) and two intercropping plantations in which jack beans are used, T14 (jack beans and corn) and T17 (jack beans, corn and castor beans) of both cycles; the accumulation of biomass, C and nutrients in the root system, as well as the rhizodeposition are lower in these treatments than in the other treatments (Figures 3 and 4), which is the main characteristic of the group. When compared to the other groups, both G4 and G5 did not show good capacity for nutrient accumulation (Table 6), and did not show the same efficiency of these in the provision of ecosystem services, since this efficiency is directly linked to the ability to cycle nutrients and produce biomass in crops.

Table 6 – Multivariate analysis of variance, means and standard deviation of variables for each group formed by cluster analysis.

Variables	G1	G2	G3	G4	G5
Rhizodeposition	1.81 ± 0.50	1.57 ± 0.20	2.49 ± 0.37	0.66 ± 0.16	1.35 ± 0.29
C S	3.77 ± 0.54	3.31 ± 0.39	2.81 ± 0.51	2.30 ± 0.96	1.70 ± 0.65
N S	91.77 ± 18.87	55.89 ± 17.47	26.92 ± 9.17	43.38 ± 15.22	41.70 ± 12.92
P S	15.15 ± 4.87	14.65 ± 5.78	15.27 ± 6.74	12.75 ± 4.65	8.32 ± 3.96
K S	133.88 ± 51.38	165.83 ± 42.99	80.93 ± 25.78	93.86 ± 27.23	64.88 ± 18.97
Ca S	120.36 ± 38.38	64.46 ± 33.11	33.95 ± 12.51	46.22 ± 16.98	56.07 ± 25.75
Mg S	31.30 ± 4.28	22.53 ± 4.46	14.88 ± 2.56	15.50 ± 5.97	11.24 ± 4.26
S S	26.12 ± 6.68	17.90 ± 6.62	12.16 ± 3.14	12.95 ± 4.13	11.14 ± 4.28
Cu S	0.12 ± 0.02	0.11 ± 0.02	0.08 ± 0.02	0.08 ± 0.03	0.05 ± 0.02
Fe S	1.67 ± 0.46	1.11 ± 0.27	0.86 ± 0.16	0.87 ± 0.25	0.75 ± 0.22
Mn S	0.53 ± 0.10	0.32 ± 0.07	0.28 ± 0.07	0.30 ± 0.09	0.19 ± 0.07
Na S	3.18 ± 0.63	2.78 ± 0.96	1.77 ± 0.20	1.71 ± 0.79	1.39 ± 0.71
C RO	1.25 ± 0.34	1.09 ± 0.14	1.73 ± 0.25	0.46 ± 0.11	0.94 ± 0.20
N RO	10.05 ± 4.90	12.91 ± 1.76	18.59 ± 4.85	5.73 ± 2.41	10.22 ± 3.19
K RO	21.73 ± 4.90	19.54 ± 4.33	32.64 ± 7.05	8.01 ± 2.12	17.99 ± 4.24
Ca RO	35.44 ± 10.21	26.18 ± 7.35	32.82 ± 8.08	11.84 ± 3.05	26.88 ± 6.77
Mg RO	2.93 ± 0.73	1.87 ± 0.38	2.34 ± 0.35	0.88 ± 0.23	1.58 ± 0.48
S RO	7.86 ± 1.89	7.24 ± 1.67	10.85 ± 2.73	2.88 ± 0.86	6.30 ± 1.65
B RO	0.57 ± 0.19	0.48 ± 0.20	1.20 ± 0.57	0.19 ± 0.05	0.33 ± 0.14
Mn RO	0.15 ± 0.05	0.13 ± 0.03	0.15 ± 0.02	0.05 ± 0.02	0.09 ± 0.03
Zn RO	0.24 ± 0.07	0.19 ± 0.03	0.25 ± 0.03	0.08 ± 0.02	0.15 ± 0.04
F Test	G1XG2 = 2,504.197** G2XG4 = 942.5011**	G1XG3 = 8,569.276** G2XG5 = 1,997.244**	G1XG4 = 3,218.922** G3XG4 = 1,765.003**	G1XG5 = 4,569.685** G3XG5 = 4,068.811**	G2XG3 = 2,966.730** G4XG5 = 51,171.92**

It is observed that, although green manure contributes to improve soil properties, the choice between the use of single crops or a combination of species will influence the capacity of the agroecosystem in the input of biomass, C, N and in nutrient cycling both on the surface and in the subsurface (Table 6). Therefore, the choice of green manures for the composition of agroecosystems when aiming at greater efficiency in the provision of ecosystem services must observe the type of service to be promoted. In this sense, this study highlights the diversity in the functions promoted by the species of green manures in relation to the addition of shoot and root biomass to the soil, as well as the nutrient cycling in the agrosystem, with the purpose of increasing biodiversity, projecting future benefits associated with agricultural production, environmental conservation, or even possible valuation systems associated with ecosystem services.

Conclusion

The addition of biomass, carbon and nitrogen and the nutrient cycling capacity were efficient variables to select green manure compositions capable of increasing the potential of providing ecosystem services of the production/agroecosystem models.

Despite single crops being more associated with provisioning services, they can stand out in isolation in nutrient cycling. Thus, depending on the specific demands of each agroecosystem, they can benefit from choosing a single species and providing support services.

Single crops should generally not be used when aiming at greater efficiency in the provision of ecosystem services by agroecosystems, except for corn and castor bean, the latter showing excellent adaptability, producing good inputs of biomass, C, N and good capacity for nutrient cycling in soil.

There is not always a positive relationship between the number of species used in consortium and the higher production of shoot and root biomass, requiring further studies on the interactions between species in the formation of consortia. The use of consortia with up to 6 species generally favored an increase in the capacity of the agroecosystem to provide provision and regulation services, with the latter associated with climate change mitigation measures, highlighting the importance of choosing the species that will be sown simultaneously.

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Contribution of authors:

Deus, T. R. V.: Investigation; Visualization; Writing — Original Draft. Giongo, V.: Conceptualization; Funding; Resources; Supervision; Project Administration; Validation; Writing — Review & Editing. Salviano, A. M.: Conceptualization; Formal Analysis; Funding; Project Administration; Acquisition; Resources; Supervision; Writing — Review & Editing. Santana, M. S.: Formal Analysis; Writing — Original Draft; SILVA, V. C.: Investigation; Writing — Original Draft. Santos, T. C.: Investigation; Visualization; Writing — Original Draft.

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