Dry mass production, nutrient accumulation and decomposition rate of cover crops intercropped with a *Theobroma cacao* full-sun system

Producción de masa seca, acumulación de nutrientes y tasa de descomposición de fitomasa de cultivos de cobertura intercalados con cacao en un sistema a pleno sol

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Abstract

Cover crops play a crucial role in promoting soil protection, enhancing organic matter content, facilitating nutrient cycling, and improving overall soil quality. The objective of this study was to evaluate the biomass production, nutrient accumulation, and decomposition rate of cover crops intercropped with *Theobroma cocoa* trees in a full-sun system. The research was conducted in Ilhéus, Bahia state, Brazil. The experimental design employed randomized blocks with three treatments, four decomposition times, and four replications. The treatments consisted of three cover crops: 1) pigeon pea (*Cajanus cajan*); 2) brachiaria (*Urochloa decumbens*); and 3) spontaneous vegetation. Decomposition rates were evaluated using litter bags at specific intervals: 0, 47, 94, 116, and 136 days after field deposition. Dry biomass production and nutrient accumulation by the cover crops were also measured. Spontaneous vegetation and brachiaria treatments exhibited the highest potassium accumulation, while no significant differences were observed among the treatments for the other evaluated nutrients. Moreover, spontaneous vegetation and brachiaria demonstrated higher decomposition rates, with 16.7% and 26.7% of the deposited material remaining at the end of the 136-day study period, respectively. In contrast, the decomposition rate of pigeon pea proved to be slower, with a remaining dry mass of 38.3%, indicating longer persistence in the soil, and consequently a greater half-life time. The cover crops investigated in this study are regarded as promising options for intercropping with cocoa, as they exhibit an average dry mass production of 10 Mg ha^{-1}. This value falls within the desired range for conservationist systems. When selecting species for intercropping, it is crucial to consider the decomposition rates these plants. This consideration ensures that the soil surface remains covered for an extended duration, leading to enhanced conservation and improvement of the soil's physical, chemical, and biological properties. Soil conservation can be effectively achieved by choosing cover crop species with slower decomposition rates, thereby contributing to the overall health and quality of the soil.

Keywords
cocoa monoculture • soil cover • Fabaceae • Poaceae

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Resumen

Los cultivos de cobertura desempeñan un papel crucial en la promoción de la protección del suelo, el aumento del contenido de materia orgánica, la facilitación del ciclo de nutrientes y la mejora de la calidad general del suelo. El objetivo del presente estudio fue evaluar la producción de biomasa, la acumulación de nutrientes y las tasas de descomposición de los cultivos de intercalados con árboles de cacao. La investigación se llevó a cabo en Ilhéus, estado de Bahía, Brasil. El diseño experimental empleó un diseño de bloques aleatorizados con tres tratamientos, cuatro tiempos de descomposición y cuatro repeticiones. Los tratamientos consistieron en tres cultivos de cobertura: 1) guandú (*Cajanus cajan*), 2) braquiaria (*Urochloa decumbens*) y 3) vegetación espontánea. Las tasas de descomposición se evaluaron utilizando bolsas de descomposición a intervalos específicos: 0, 47, 94, 116 y 136 días después de la deposición en el campo. Se evaluó la producción de biomasa seca y la acumulación de nutrientes por los cultivos de cobertura. La producción promedio de biomasa seca fue de 10 Mg ha^{-1}. Los tratamientos de vegetación espontánea y braquiaria mostraron la mayor acumulación del nutriente potasio. La vegetación espontánea y la braquiaria demostraron tasas de descomposición más altas, con 16,7% y 26,7% de material remanente después de 136 días de estudio. Por el contrario, la descomposición del guandú resultó en una persistencia más prolongada, con una masa seca restante de 38,3%, en consecuencia, un mayor tiempo de vida media. Los cultivos de cobertura investigados en este estudio se consideran opciones prometedoras para la intercalación con cacao, ya que exhiben una producción de masa seca promedio de 10 Mg ha^{-1}. Este valor se encuentra dentro del rango deseado para los sistemas conservacionistas. Al seleccionar especies para la intercalación, es crucial considerar las tasas de descomposición de estas plantas. Esta consideración asegura que la superficie del suelo permanezca cubierta durante un período prolongado, lo que conduce a una mejora en la conservación y las propiedades físicas, químicas y biológicas del suelo. Al elegir especies de cultivos de cobertura con tasas de descomposición más lentas, se puede lograr una conservación efectiva del suelo, contribuyendo así a la salud y calidad general del mismo.

Palabras clave

monocultivo de cacao • cobertura del suelo • Fabaceae • Poaceae

Introduction

The cocoa tree (*Theobroma cacao* L.) is a plant species native to the Amazon and cultivated in tropical countries of South America, West and Central Africa, India, and Southeast Asia, holding significant economic importance in several countries (17). World cocoa production is concentrated in a few key countries, such as Ivory Coast, Ghana, Indonesia, Nigeria, Ecuador, Cameroon, and Brazil, which collectively account for 88% of global production. Ivory Coast is the largest contributor, producing approximately 39% of the total (14). Brazil stands as the largest cocoa producer in South America and the seventh-largest producer globally, having reported a production of 280 thousand tons in 2021 with a planted area of 617 thousand hectares (14).

Cocoa cultivation in Brazil is predominantly concentrated in four states: Bahia, Pará, Espírito Santo and Rondônia, with Bahia being the leading producer, accounting for 100,864 tons in 2020 (4). Moreover, cocoa farming represents the most important economic activity in the southern region of Bahia. Cocoa is predominantly grown in an Agroforestry System in southern Bahia, where the cocoa tree is cultivated in the understory of the native Atlantic Forest, locally referred to as "*cabruca*" (33). Another cultivation system that has been gaining prominence is monoculture, also known as full-sun cultivation. In this case, the cocoa tree shading is temporary, only occurring in the initial growth phase, and then the entire crop cycle occurs in full sun. This system is used in countries considered as the largest cocoa producers in the world (34), and has been gaining ground in Brazil, including in non-traditional regions for cocoa cultivation.

Cover crops can be used to promote maintained soil quality and conservation in the full-sun cocoa system. The association of perennial fruit trees with cover crops is already a consolidated agricultural practice (12, 25, 27, 28, 30, 42), however, it has not yet been studied in consortium with cocoa trees in a full-sun system, warranting the need for studies to validate the production of phytomass, nutrient accumulation and the decomposition rate of cover crops. Among the various benefits, these plants can provide soil protection through litter accumulation, promote nutrient cycling, increase biological activity, enhance infiltration, and improve water storage in the soil (5, 25, 27, 29, 42), as well as increase the production of commercial crops, as verified for citrus (19), and banana (20, 29).

Crop residue accumulation on the soil surface is influenced by the decomposition rate of cover crops, which in turn is regulated by the physical and chemical conditions of the soil, the material composition that is supplied, the presence of edaphic fauna, microbial activity of the soil, and precipitation (47). In a study conducted in the Cerrado biome of Goiânia, Brazil, the decomposition rates for pigeon pea (*Cajanus cajan*) were found to be 62% 60 days after the deposition of litter bags in the field (38). Also in the Cerrado biome of Piauí state, Brazil, the decomposition rate at 314 days after cutting was 83% for *Urochloa ruziziensis* and 79% for pigeon pea (41). The dry matter production and decomposition of *Zea mays* and *Urochloa ruziziensis* straw were additionally evaluated in an integrated crop-livestock system. The obtained dry mass was 6.6 Mg ha^{-1} and the half-life time was 115 days. At the end of the study, 36% of the crop residue was on the soil, with a loss of 4.23 Mg ha^{-1} of dry matter (36).

Cover crops are widely used in intercrops with fruit trees, especially species of brachiaria, and pigeon pea as an option for Poaceas and Fabaceas, respectively. However, the use of cover crops in full-sun cocoa systems has not yet been studied. Therefore, the present study was carried out with the hypothesis that pigeon pea (*Cajanus cajan*) in consortium with full-sun cocoa exhibit an accelerated decomposition rate compared to brachiaria (*Urochloa decumbens*) and spontaneous vegetation. The objective of the present study was to evaluate the phytomass production, nutrient accumulation, and decomposition rate of cover crops intercropped with cocoa trees cultivated in a full-sun system.

Materials and methods

Characterization of the study area

The experiment was conducted at the cocoa research center (CEPEC-CEPLAC), in Ilhéus, Bahia state, Brazil. The site was located at coordinates 14°47'55" S and 39°02'01" W. According to the Köppen climate classification, the region has an Af-type hot and humid tropical forest climate, without a distinct dry season. The average annual precipitation exceeds 1,300 mm, distributed throughout the year, with an average temperature of 23°C and relative humidity of 80%. Climatic data, including temperature and precipitation, were recorded at the CEPLAC/CEPEC/SERAM meteorological station during the experiment (figure 1, page XXX).

The regional topography is characterized as undulating, with an altitude of 60 m. The experimental area soil is classified as a Typic Hapludalfs (34). The soil particle size distribution was 320 g kg^{-1} sand, 338 g kg^{-1} silt and 342 g kg^{-1} clay. The chemical properties of the soil before implementing the experiment are presented in table 1 (page XXX).

Experimental area history

The experimental area (2000 m^2) was initially maintained until 2016 in an agroforestry system of cocoa with *Erythrina* spp. This previous system was then subjected to clearcutting to implement a monoculture cocoa. All plant residues were removed from the site, and subsoiling was carried out to a depth of 0.50 m, followed by harrowing to incorporate phosphate fertilization (144 kg ha^{-1} of P_2O_5) applied in the form of single superphosphate. Liming was not used due to low active acidity and adequate levels of Ca and Mg in the soil. The area remained fallow until 2019, during which time spontaneous vegetation growth occurred.

Source: Meteorological station of CEPLAC/CEPEC/SERAM.

Fuente: Estación meteorológica de CEPLAC/CEPEC/SERAM.

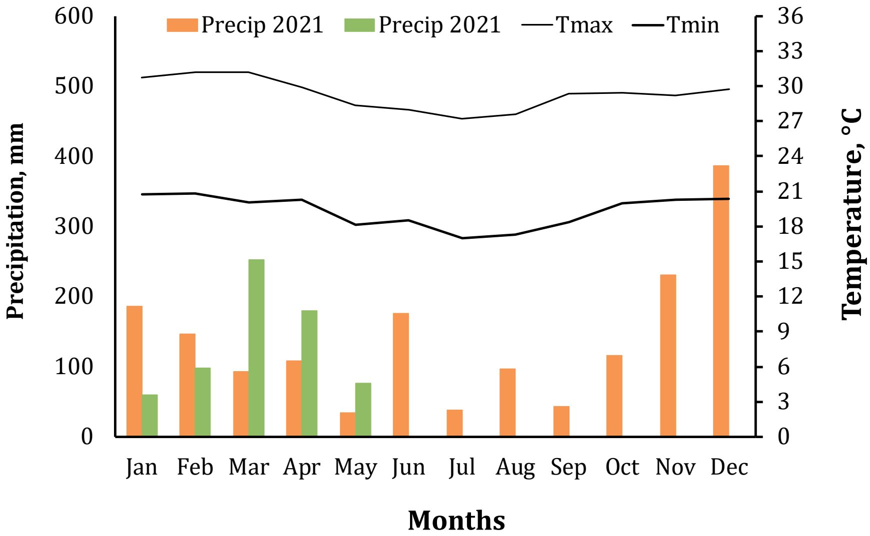

Figure 1. Meteorological data from the study period (December 2021 to May 2022).

Figura 1. Datos meteorológicos del período de estudio (diciembre de 2021 a mayo de 2022).

Table 1. Soil chemical attributes before the experiment implemented in the 0-20 cm layer.

Tabla 1. Atributos químicos del suelo antes de que se implementara el experimento en la capa de 0-20 cm.

pH	H+Al	Al	Ca	Mg	SB	T	P	B	S	K	Cu	Fe	Mn	Zn	V	m
	---------------- $cmol_c\ dm^{-3}$ --------------						-------------- $mg\ dm^{-3}$ --------------								---%---	
6.1	4.2	0	7.5	2.1	9.9	9.9	40	0.65	7	78	4.9	84	489	10	70	0

H+Al: potential acidity; Al: aluminum; Ca: calcium; Mg: magnesium; P: phosphorus; SB: sum of bases; T: CTC a pH 7; S: sulfur; K: potassium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; B: boron; V: base saturation; m: aluminum saturation.

H+Al: acidez potencial; Al: aluminio; Ca: calcio; Mg: magnesio; P: fósforo; SB: suma de bases; T: CTC a pH 7; S: azufre; K: potasio; Cu: cobre; Fe: hierro; Mn: manganeso; Zn: zinc; B: boro; V: saturación de bases; m: saturación de aluminio.

Then all vegetation was cut (full mowing with brush cutter) in July 2019, and soil surface was maintained with straw. Seedlings (6 months old) produced by cuttings from plagiotropic branches of the cacao CEPEC 2002 clone were planted in holes with dimensions 0.40 x 0.40 x 0.40 m, with spacing of 1.5m between plants and 4 m inter-rows.

Experimental design and treatments

The experiment was conducted in a randomized complete block design with four replications. The experimental plots had an area of 9 m x 12 m, totaling 108 m^2, with 18 cocoa trees by plot. One harrowing operation was performed in all inter-rows of the cacao trees, followed by manual sowing and incorporation of cover crop seeds. The cover crops implemented in March 2020 were: 1) Brachiaria (*Urochloa decumbens*); (2) Crotalaria (*Crotalaria breviflora*); and (3) Spontaneous vegetation. The following seed quantities were used: Brachiaria: 3.5 kg ha^{-1} and Crotalaria: 15 kg ha^{-1}. The spontaneous vegetation consisted of germinating the existing seed bank on the site, without the addition of external seeds.

In March of 2021, the evaluation year of this study, the crotalaria treatment was replaced by pigeon pea (*Cajanus cajan) variety IAPAR 43*, utilizing a seed rate of 45 kg ha^{-1}. There was no need to replant Brachiaria and spontaneous vegetation treatments in 2021, as the plants persisted in the plots. The spontaneous vegetation treatment consisted of local native species, predominantly including *Commelina benghalensis* L. (10%); *Bidens pilosa* L. (3%); *Cyperus ferax* (6%); *Euphorbia heterophylla* L. (5%); *Rhynchospora nervosa* (6%); *Panicum maximum* L. (40%); and *Sorghum arundinaceum* (30%), with the latter two species having the greatest occurrence.

The experiment evaluated three cover crop treatments and their decomposition rates: (1) Brachiaria; (2) pigeon pea; and (3) spontaneous vegetation. The decomposition periods refer to the days (0, 47, 94, 116 and 136) that the cover crop residues remained in the field.

Determination of dry mass and nutrient accumulation of cover crops

The cover crop biomass was sampled in July 2021, four months after sowing the pigeon pea treatment. A 0.5 m × 0.5 m metallic square was randomly thrown into each plot (10) and all plant material within the square was cut close to the ground. The collected plant material was dried in an oven at 65°C for 72 hours to determine the dry mass production. Next, the nutritional composition of the dried plant samples was analyzed to evaluate the nutrient accumulation in the cover crops. The nitrogen (N); phosphorus (P); potassium (K); calcium (Ca); magnesium (Mg); sulfur (S); iron (Fe); zinc (Zn); copper (Cu); manganese (Mn) and boron (B) concentrations were determined (17). The nutrient accumulation was calculated by multiplying the dry mass and the respective nutrient concentrations in the cover crop biomass (21, 41).

The cover crop shoot management was performed with a brush cutter, and the residues were maintained on the soil surface. The mowings were repeated in the following months from July 2020: September 2020, November 2020, January 2021, March 2021, July 2021, September 2021, November 2021, January 2022 and March 2022. Two annual fertilizations were performed on the cocoa tree after cutting the cover crops at a dose of 50 kg ha^{-1} of N per application in the form of urea in July and January of each year (2020 and 2021). No other fertilizations were carried out, neither for the cocoa tree nor the cover crops.

Decomposition rate of cover crops

The plant material collected in July 2021 was separated according to each cover crop treatment and then dried in an oven. Afterwards, it was fragmented into pieces of approximately five centimeters. Portions of 11 g of the fragmented plant material were weighed and packed in litter bags. The litter bags were made with nylon fabric, with a mesh size of 2 mm and dimensions of 0.20 m x 0.20 m. Four litter bags for each cover crop treatment were distributed in the rows of cocoa trees in each experimental plot in direct contact with the soil surface. The decomposition rate of the cover crop residues was evaluated in the field during December 2021 to April 2022. The following litter bag collection times were considered: 0, 47, 94, 116 and 136 days after deposition in the field. A litter bag was collected from each treatment after each period. The material was removed from the litter bag, and washed in distilled water under a screen through a 0.053 mm mesh to remove soil particles. The material was then dried in a forced-air circulation oven at 65°C until reaching constant weight (45). Finally, the material was weighed to obtain the remaining dry mass. The remaining mass percentage (R%) was calculated using the relationship between the final dry weight (Wf) and the initial dry weight (Wi), according to the expression: R%= (Wf/Wi) x 100. The exponential model proposed in equation (1) was used to describe the decomposition rate of the residues (44).

$$X = X_0 . e^{-kt} \quad (1)$$

were:

X = amount of dry phytomass remaining after a period of time t, in days

X_0 = initial amount of dry phytomass

k = residue decomposition constant

The half-life time was calculated using the value of k, which represents the time required for the decomposition of half of the initial plant residues. This was obtained through the simple exponential linearization model (18), calculated by equation (2).

$$T_{\frac{1}{2}} = \frac{0.69315}{k} \quad (2)$$

Chemical characterization of residues after decomposition

The material remaining in the litter bag collected after the final decomposition period was washed and dried in an oven at 65°C for chemical characterization. Three subsamples of each treatment were separated, ground and the total nitrogen content was determined by the Kjeldahl method (13). Additionally, the lignin and cellulose concentrations were determined using the acid detergent fiber (ADF) method (48).

Statistical analysis

The data analysis was conducted considering the following factors: treatment (cover crops); the decomposition period and characterization of the residues after decomposition; the collection time of the litter bags; and the interaction of these factors. The data were analyzed for homogeneity of error variances by the Cochran test and normality by the Lilliefors test, followed by analysis of variance (ANOVA); mean comparison in significant cases was applied by the Tukey's test ($p<0.05$), using the RStudio program, version 3.5.0 (R-Development Core Team 2019).

Results and discussion

The precipitation in the period which included the growth of cover crops (March to June 2021) was 412mm and the temperature ranged from 31°C to 18°C (figure 1, page XXX).

Dry mass production and nutrient accumulation

Higher dry mass production was observed in the brachiaria treatment (11.9 Mg ha^{-1}), followed by spontaneous vegetation (10.3 Mg ha^{-1}) and pigeon pea (7.9 Mg ha^{-1}) (figure 2).

Equal letters indicate no difference between treatments by Tukey's test ($p<0.05$). The bars represent the standard error of the means.

Letras iguales indican que no hay diferencias entre tratamientos según la prueba de Tukey ($p<0,05$). Las barras indican los valores del error estándar de las medias.

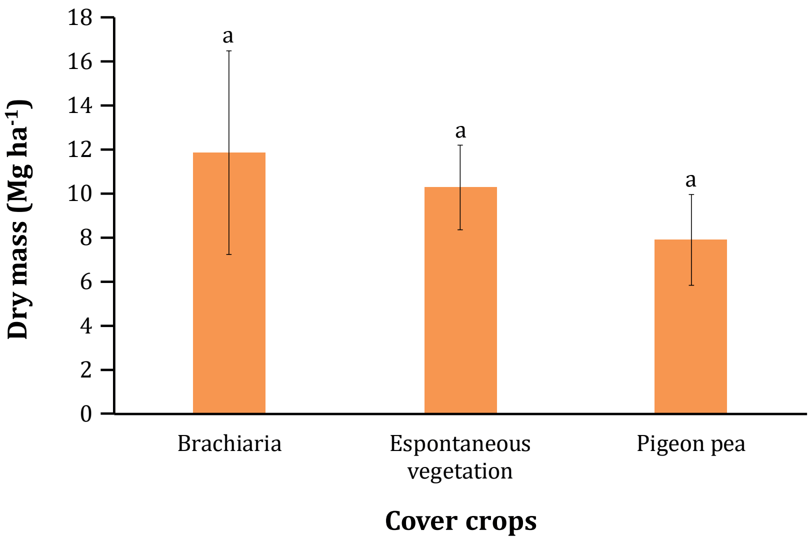

Figure 2. Dry mass production (March - July 2021) of cover crops intercropped with cocoa trees.

Figura 2. Producción de masa seca (Marzo - Julio 2021) de cultivos de cobertura intercalados con cacao.

The dry matter production in the three treatments is considered adequate for conservationist agricultural systems, as the values were between 6 Mg ha^{-1} and 12 Mg ha^{-1}, which is the average amount necessary to provide sufficient soil coverage and ensure beneficial effects on the physical, chemical, and biological attributes of the soil, especially in tropical climate regions (1, 43).

It is important to note that the dry mass production is influenced by the location and time of cultivation, climatic conditions, soil fertility, species used, and cutting age (24, 39). These factors (table 1, page XXX and figure 2, page XXX) were also responsible for the dry mass production obtained in the present study. A study (23) in the municipality of Diamantina, Minas Gerais state, Brazil, implementing a no-tilling system using cover crops observed a dry mass of 4.54 Mg ha^{-1} for spontaneous vegetation and 4 Mg ha^{-1} for pigeon pea, constituting lower values than those observed in the current study (10.3 and 7.9 Mg ha^{-1} for spontaneous vegetation and pigeon pea, respectively). These same authors reported a production of 11.2 Mg ha^{-1} for *Urochloa decumbens*, which is a similar result to that found in the present investigation. Regarding the spontaneous vegetation treatment, the high dry mass production observed in this study can also be attributed to the occurrence of two grasses with great biomass production capacity, *Panicum maximum* L. and *Sorghum arundinaceum*, present in the experimental area. Furthermore, the adequate precipitation conditions during the growth of cover crops (figure 1, page XXX) were a key factor in the dry mass achieved (24, 28, 39).

When evaluating different cover crop species in an orange orchard in Cruz das Almas, Bahia state, Brazil, Carvalho *et al.* (2021) reported the highest dry matter production of 11 Mg ha^{-1} for *Urochloa decumbens* and *Urochloa ruzizienses*. In this same study, spontaneous vegetation had the lowest dry matter production, which differs from the results of the current investigation. The discrepancy in the performance of spontaneous vegetation between the two studies could be attributed to differences in factors such as soil fertility, climatic conditions, and the specific species composition of the spontaneous vegetation (23, 28, 39).

Significant differences regarding nutrient accumulation (table 2) were only observed for potassium (K^+). The spontaneous vegetation treatment exhibited the highest K^+ accumulation, reaching 359 kg ha^{-1}, which was significantly greater than the pigeon pea treatment, presenting the lowest K^+ accumulation at 88 kg ha^{-1}. A substantial K^+ accumulation was also observed in the Brachiaria treatment, although it did not differ significantly from the other treatments. The results indicate a direct relationship between potassium accumulation by the treatment and dry matter production (figure 2, page XXX and table 2). The K^+ accumulation in the spontaneous vegetation was approximately five times greater than that of the pigeon pea treatment. The high dry matter production and considerable K^+ accumulation in the spontaneous vegetation suggest that this treatment may provide similar nutrient cycling benefits as those observed with purposefully cultivated cover crops species (39). Therefore, when spontaneous plant communities possess the characteristics of high biomass production and nutrient accumulation, they can be considered viable alternatives for cover cropping, as they can deliver the benefits of implanted species without the establishment cost.

Table 2. Nutrient accumulation (March-July 2021) of cover crops intercropped with cocoa trees.

Tabla 2. Acumulación de nutrientes (Marzo-Julio 2021) de plantas de cobertura intercaladas con cacao.

Cover crops	N	P	K	Ca	Mg	S	Fe	Zn	Cu	Mn	B
	kg ha^{-1}										
Espontaneous vegetation	224	49	359a	91	53	18	1.05	0.47	0.10	1.54	0.15
Pigeon pea	228	23	88b	32	13	7	0.57	0.17	0.05	0.39	0.10
Brachiaria	167	43	211ab	49	41	24	1.63	0.52	0.08	0.96	0.12

Averages followed by the same letter in the columns do not differ from each other, ns: not significant by Tukey's test ($p<0.05$). N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; S: sulfur; Fe: iron; Zn: zinc; Cu: copper; Mn: manganese; B: boron.

Promedios seguidos por la misma letra en las columnas no difieren entre sí, ns: no significativo por la prueba de Tukey ($p<0,05$). N: nitrógeno; P: fósforo; K: potasio; Ca: calcio; Mg: magnesio; S: azufre; Fe: hierro; Zn: zinc; Cu: cobre; Mn: manganeso; B: boro.

Forage grasses are reported to exhibit great potential for K^+ absorption and subsequent accumulation, which is then returned to the soil following the decomposition of plant residues (6). Grasses in no-tillage systems can leverage their deep root system, remove nutrients from depth and subsequently return them to the soil surface through decomposition of their plant residues (36). Studies indicate that brachiaria grasses are highly efficient in K^+ cycling, corroborating the observations made in the present study (22, 40, 45). It is noteworthy that high values regarding nitrogen (N) accumulation were observed across the treatments, ranging from 167 to 228 kg ha^{-1}, although no statistically significant differences were detected (table 2, page XXX). The ability of cover crops to accumulate N is primarily dependent on the specific species used (32). In a study conducted in the state of Piauí, Brazil, the N accumulation observed for pigeon pea was similar to the values reported in the current study (260 kg ha^{-1}); however, the accumulated N value for brachiaria (*Urochloa ruziziensis*) was higher compared to the present findings (253 kg ha^{-1}) (41).

Decomposition rate and half-life ($T_{1/2}$)

The decomposition of cover crop residues decreased exponentially over time. During the 136-day evaluation period, the pigeon pea treatment exhibited the lowest loss of dry mass in its residues. In contrast, the Brachiaria and spontaneous vegetation treatments showed greater degradation of their residues, with similar patterns observed between these two treatments (figure 3).

Different lowercase letters indicate differences between treatments for remaining dry mass on the same day of decomposition, by Tukey's test ($p<0.05$).

Diferentes letras minúsculas indican diferencias entre tratamientos para masa seca remanente, el mismo día de descomposición, utilizando la prueba de Tukey ($p<0,05$).

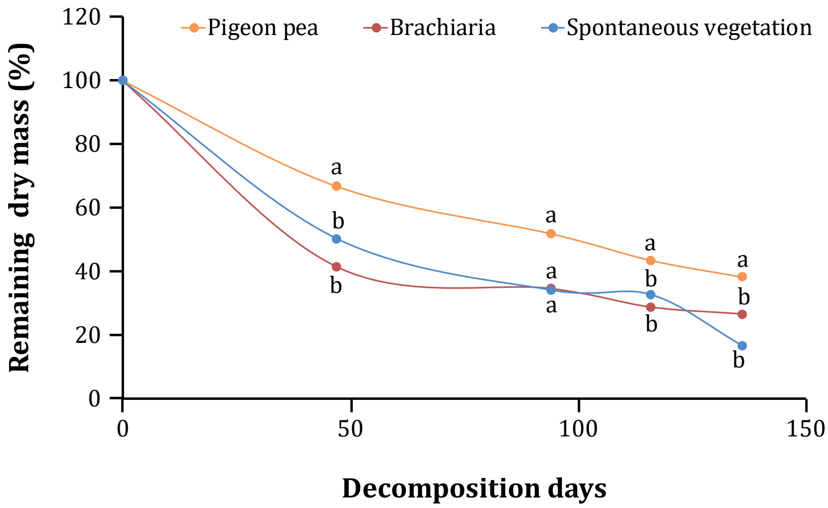

Figure 3. Remaining dry mass (%) of cover crops, intercropped with cocoa trees.

Figura 3. Masa seca restante (%) de cultivos de cobertura, intercalados con árboles de cacao.

The highest decomposition rates were observed for brachiaria and spontaneous vegetation treatments, with only 41.5% and 50.4% of residues remaining, respectively, in the first 47 days after deposition in the field (figure 3). These treatments differed significantly from the pigeon pea treatment for this evaluation period, which exhibited a higher residue remaining percentage of 66.8% (figure 3). By the end of the evaluation period (136 days), the spontaneous vegetation and brachiaria treatments continued to display the highest decomposition rates, with only 16.7% and 26.7% of the deposited material remaining, respectively. These values differed from the pigeon pea treatment, which had the highest remaining dry mass on the soil of 38.3% (figure 3).

In evaluating the decomposition rate of cover crops in the Cerrado biome, it was observed that the pigeon pea treatment exhibited a higher remaining dry mass (37%) after 154 days of deposition compared to spontaneous vegetation (23%) and brachiaria (21%) (46), corroborating what was observed in the present study. However, a contradictory result was observed in a study conducted in the Cerrado, Góias state, Brazil. In this aforementioned study, high decomposition rates were reported for Brachiaria (48%) and pigeon pea (65%) 150 days after cutting (16), constituting contrasting results to what was observed in our study, especially for pigeon pea. The authors suggest that the elevated decomposition rate in this case may have been driven by the soil being maintained in a moist condition through irrigation during the decomposition period.

The spontaneous vegetation and brachiaria treatments displayed the highest decomposition coefficient (k) of 0.011496 g g^{-1} d^{-1} and 0.009154 g g^{-1} d^{-1}, respectively. Consequently, these treatments also exhibited the shortest half-life times ($T_{1/2}$) of 60 and 75 days, indicating that half of the residues had decomposed by those time points (table 3).

Table 3. Decomposition coefficient (k) and half-life time ($T_{1/2}$) of cover crops intercropped with cocoa.

Tabla 3. Coeficiente de descomposición (k) y tiempo de vida media ($T_{1/2}$) de cultivos de cobertura intercalados con cacao.

Cover crops	k (g g^{-1} d^{-1})	$T_{1/2}$ (days)
Pigeon pea	0.006869	100
Brachiaria	0.009154	75
Spontaneous vegetation	0.011496	60

The pigeon pea exhibited a lower decomposition coefficient (k), resulting in an estimated $T_{1/2}$ of 100 days. Various factors influence the decomposition rate of plant residues, with the chemical composition being one of these factors. The higher the C/N ratio and higher cellulose, hemicellulose, lignin, and polyphenols levels in the plant constituents lead to slower decomposition of phytomass (2, 37). In a study conducted to evaluate the decomposition rate of cover crops in the Cerrado region during the 2001/2002 period, it was observed that the $T_{1/2}$ for brachiaria was 78 days, while for pigeon pea it was 101 days (45). This finding aligns with the results obtained in the present study. The same authors also mention that Fabaceae plants in uncovered Cerrado soil exhibited slower decomposition compared to grasses.

The extended persistence of pigeon pea residues in the soil can be attributed to its composition, characterized by a significant proportion of lignified stems that impede rapid decomposition. This assertion is supported by the analysis conducted on plant residues after the deposition period in the field, as outlined in table 4 (page XXX). Pigeon pea and spontaneous vegetation exhibited the highest lignin contents, which differed significantly from brachiaria, showing the lowest lignin contents. It is worth noting that cover crops cut during flowering stages tend to have higher hemicellulose and lignin concentrations (8). The same authors also reported higher lignin concentrations during flowering for *Cajanus cajan*, a species that displayed a slower decomposition rate. The same occurred in this study for pigeon pea, which exhibited elevated lignin concentrations (table 4, page XXX) and a reduced decomposition rate (figure 3, page XXX). In contrast, the spontaneous vegetation presented high lignin content and a rapid decomposition rate.

The chemical composition of plant residues, including lignin, cellulose, hemicellulose, and polyphenols, as well as the C/N ratio and the lignin:N ratio, play a significant role in the decomposition process. Lignin presents a challenge to decomposition due to its resistance and impermeability to microbial attack in plant tissues (7, 9). In a study conducted by the same authors, the lignin contents of cover crops species were assessed, with the highest concentration observed in pigeon pea *cv*. mandarin. Conversely, *Brachiaria ruziziensis* exhibited the lowest lignin concentration. This composition, contributes to the slower decomposition rate of pigeon pea and the faster decomposition rate of brachiaria. The degradation process is hindered by the presence of lignin because only a limited number of microorganisms possess the necessary enzymes to break down its chemical bonds (15).

Table 4. Nitrogen, cellulose, and lignin concentrations in cover crop residues after 136 days deposited in the field.

Tabla 4. Concentración de nitrógeno, celulosa y lignina en residuos de cultivos de cobertura después de 136 días depositados en el campo.

Cover crops	Nitrogen	Celullose	Lignin
	g kg^{-1}		
Brachiaria	1.25 b	323.2 a	153.7 b
Pigeon pea	1.37 b	429.6 a	277.9 a
Spontaneous vegetation	2.02 a	292.7 a	285.9 a

Means followed by the same letter in the columns do not differ from each other by the Tukey's test (p<0.05).

Los promedios seguidos por la misma letra en las columnas no difieren entre sí por la prueba de Tukey (p<0,05).

In addition to lignin, nitrogen also plays a significant role in the decomposition process. The spontaneous vegetation treatment presented the highest nitrogen contents, which differed from the other treatments, as indicated in table 4. Higher nitrogen concentrations in plant tissues enable microorganisms to oxidize amide bonds (NH_2) of organic molecules. This process provides energy for microbial growth and facilitates decomposition (3). The presence of higher nitrogen levels in the spontaneous vegetation treatment justifies the observed remaining dry mass at the end of the study, which was similar to that of the brachiaria treatment, despite having similar lignin contents to pigeon pea. The increased nitrogen levels in spontaneous vegetation promoted greater microbial activity in the plant tissue, thereby facilitating decomposition even in the presence of lignin levels.

Conclusions

The cover crops investigated in this study are regarded as promising options for intercropping with cocoa, as they exhibit an average dry mass production of 10 Mg ha^{-1}. This value falls within the desired range for conservationist systems. When selecting species for intercropping, it is crucial to consider the decomposition rates these plants. This consideration ensures that the soil surface remains covered for an extended duration, leading to enhanced conservation and improvement of the soil's physical, chemical, and biological properties. Soil conservation can be achieved by choosing cover crop species with slower decomposition rates, in turn contributing to the overall health and quality of the soil.

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