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Chemical Properties of Soil and Cassava Yield as a Function of Weed Management by Cover Crops in the Amazon Ecosystem

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Abstract: Cassava (*Manihot esculenta*) yields are severely affected by the interference of weed plants. Using cover crops for weed control appears as a sustainable alternative practice because it maintains the soil covered and reduces the need for herbicides. The aim of this study was to assess cassava crop yields and the soil chemical properties as a function of use of cover crops for weed management. Treatments were three cover crops (*Brachiaria ruziziensis*, *Canavalia ensiformis*, and *Mucuna pruriens*), chemical control, mechanical control, and treatment with no weed control. Cover crops reduced the diversity of species and the quantity of individuals of the weed community in cassava cultivation. The treatments with chemical and physical weed control achieved higher yields. The cover crops *B. ruziziensis* and *C. ensiformis* increased cassava yields by 30% and 14%, respectively, when compared with the treatment with no control. The cover crops increased the pH, MO, K, Ca, and Mg values when compared with the treatments with chemical and mechanical weed control. *Brachiaria ruziziensis* and *C. ensiformis* are recommended as a cover plants in cassava production systems in the Amazon region. The use of cover crops associated with cassava is a sustainable management option because, in addition to the suppressive effect on weeds, cover crops improve the chemical properties of soil, which may contribute to increasing cassava production in the long term.

Keywords: *Brachiaria ruziziensis* (syn. *Urochloa ruziziensis*); *Canavalia ensiformis*; *Manihot esculenta*; *Mucuna pruriens*; soil fertility; weed control

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1. Introduction

Studies addressing sustainable alternatives for vegetable production are important, especially in the Amazon region, where preservation of the ecosystem is essential to maintain biodiversity. Cassava is a plant native to the Amazon region which belongs to the family Euphorbiaceae and the genus *Manihot* [1].

In the state of Amazonas, cassava is mainly cultivated by small farmers, and most of the production is destined to subsistence and animal feeding. Due to the high level of rusticity of this culture and low technology required for cultivation, many cassava growers underestimate the need for weed control. However, when not managed properly, weed plants constitute a major limiting factor for cassava production and contribute to the low crop yields found in the state of Amazonas (9.83 t ha^{-1}), in contrast with other Brazilian states, including those in the North region, of about 20 t ha^{-1} [2].

With respect to weed management by local producers, when not neglected, control is achieved by manual weeding, using hoes, a practice that is not totally viable due to the shortage of labor in addition to the weather conditions, such as high humidity and temperatures, which make it difficult to perform this practice [3]. For this reason, producers have been increasingly interested in using herbicides due to the small number of workers required, in addition to the high control efficacy and low production costs. The increasing use of herbicides in Amazonia crops deserves attention, considering that the inadequate use of these products may cause irreversible environmental damages [4].

The integration of grass and legume as cover crops into the cropping system can bring numerous benefits to the soil, such as an increased availability of nutrients, soil organic carbon, total nitrogen, and reduced nitrate leaching and soil loss [5–7]. Improvements in soil chemical properties may contribute to a greater development of shoots and faster canopy closure and, consequently, more shading on weeds, reducing the interference of these plants with cassava [8].

However, recommendations of cover crops for a given culture depend on practical studies and fine adjustments that consider the characteristics of the crop, the cover crops used, the composition of the weeding community, climate, and the local reality. Studies investigating the effects of cover crops on productivity and on the chemical properties of soil in cultivated crops in Amazonia are still incipient.

Thus, the objective of this research was to examine the effects of cover crops and chemical and mechanical controls on cassava yields and on the chemical properties of soil, aiming at the incorporation of good practices in cassava cropping systems, promoting sustainability and food security.

2. Materials and Methods

Two experiments were conducted at the Experimental Farm of the Federal University of Amazonas (Latitude: 02°37′17.100′′ and 02°39′41.400′′ S; Longitude: 60°03′29.100′′ and 60°07′57.500′′ W), state of Amazonas, Brazil, in two growing seasons, 2018/2019 and 2019/2020. The climate is "Am" type, according to Köppen classification [9,10], humid tropical, with air relative humidity around 89%, annual rainfall around 2000 mm.

The experimental area was prepared with light harrowing and fertilization as recommended for cassava cultivation in the region [11]. The cultivar chosen was *Manteiga*, considered sweet cassava, which has a 12-month cycle, average yield of 15 t ha^{-1} and hydrocyanic acid concentration below 50 mg kg^{-1} [12].

Propagation was made with stem cuttings of 10 to 15 cm in length from adult cassava plants, with 3 to 6 bud eyes, called *manivas* in the region. The stem cuttings (*manivas*) were deposited horizontally in 10-cm deep bed furrows and covered with earth. Spacing was 1 m between rows and between plants, totaling 10,000 plants ha^{-1}.

The experiment was conducted in a randomized block design with six treatments and four replicates. Each plot was made up of five planting rows, with six plants per row, totaling thirty plants per plot. The net area of each plot comprised the central region of the plot, using three central lines and disregarding the border plants, totaling 12 useful plants for assessment. Treatments were three cover crop species (*Brachiaria ruziziensis*, *Canavalia ensiformis*, and *Mucuna pruriens*); chemical control with herbicide; mechanical control; and treatment with no weed control. The chemical and mechanical weed controls were conducted 3 months after planting, with 2-month intervals, totaling 5 operations for both.

Surveys on the floristic and phytosociological composition of the weed plants were carried out prior to implementation of the experiment and at its completion, using quadrat samplers with an area of 0.12 m^2, which were placed at random twice on each plot, totaling 0.96 m^2 of sampled area per treatment and 5.76 m^2 of total sampled area for each year. The calculated phytosociological parameters were relative frequency, relative density, relative abundance and the importance value index (IVI), as proposed by Mueller-Dombois and Ellenberg [13].

As the initial growth stage of cassava favors the emergence and interference of weeds [8,14], the cover crops were planted three months after planting cassava to minimize the risks of interference. Planting density was 9 kg ha^{-1} for *B. ruziziensis*, and 80 kg ha^{-1} for *C. ensiformis* and *M. pruriens*. The grass plants were planted in furrows between the cassava planting lines, while legumes were planted in 3–6 cm deep holes 40 cm apart.

All cover plants were sown at a distance of 30 cm from the cassava rows to reduce risks of interference.

In the chemical control treatment, glyphosate (480 g a.i. ha^{-1}) was directedly sprayed at post-emergence, using an automated back sprayer, pump pressure of 40 to 60 lb pol^{-1}, nozzle 80.04, with a dosage of 3.5 L ha^{-1}. The mechanical control consisted of hoeing for weed suppression.

At 360 days after planting, the period that corresponds to the completion of the cassava growth cycle, yields were assessed by weighing the roots of the plants grown in the net area of each treatment. The roots were cleaned with water, carefully peeled and immediately weighed to obtain fresh weight and, afterwards, were dried in forced-air circulation oven at 65 °C for 72 h, or to reach constant weight. Production values were converted to yield, expressed in tons ha^{-1}, using the formula: yield (t ha^{-1}) = weight (kg) of root of 12 useful plants × 10,000 plants × $twelve^{-1}$.

At harvest, the plant mean height, stem diameter, shoot dry weight, and root counts per plant were determined. The mean height of the plants, determined at harvest, consisted of the distance between the tip of the stem base to the tip of the highest shoot. The stem diameter was determined by measuring the basal diameter at 5 cm above the ground using a caliper. The usable plants from each plot were cut at the ground level, and the vegetable tissues were chopped and placed in a forced-air circulation oven at 65 °C for 72 h, or until reaching constant weight, and their sum was used to estimate the shoot dry weight and the values were transformed into tons ha^{-1}.

The soil samples were collected using a hand auger from the 0–20 cm depth at the end of each experiment. The concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), pH, organic matter (MO), and potential acidity (H + Al), were determined according to the methodology proposed by Raij and Quaggio [15].

The resulting data were subjected to analysis of variance, and the F-test was applied, and the means were compared by the Tukey test at 5% probability level. Statistical analyses were carried out using the statistical software program RStudio, version 1.3.1093 [16].

3. Results and Discussion

3.1. Phytosociological Parameters of Weeds

In the first phytosociological survey, 962 individuals were recorded, distributed into 16 species, belonging to nine botanical families. The Poaceae family was the most representative, with five species, followed by Cyperaceae, Fabaceae, and Verbenaceae families, each one with two species (Table 1). The importance of the Poaceae family for crops grown in the country has already been observed in other studies involving weed plants in crops in the Amazon region, e.g., Fontes et al. [17], Da Gama et al. [18], Damasceno [19], De Almeida et al. [20], Dos Santos [21], Miléo et al. [22], and Albertino et al. [23].

Concerning classes, there was a balance between the number of monocotyledon and dicotyledon species, each one with eight species. However, there was a predominance of monocotyledons in the first year (83.05%), mainly due to the high number of individuals of the *Axonopus affinis* and *Paspalum multicaule* species, which together represented more than 70% of the individuals found.

Concerning species, the highest IVI was achieved by *A. affinis* (84.81), mainly due to the total number of individuals and high relative density. This is a perennial, stoloniferous, creeping, fast-growing grass species, tolerant to cutting and trampling, which is considered difficult to control due to the high rooting capacity of its stolons [24].

This species was also identified by Miléo et al. [22] in a cassava cultivated field in the state of Amazonas, where a high IVI for *A. affinis* was found. Likewise, the study conducted by Da Gama et al. [18] showed that a species of the genus *Axonopus* achieved the highest IVI in guarana culture.

At the end of the first year of the experiment, changes in the floristic composition of the weed plants were observed, with the emergence of new species, while other species disappeared (Table 2).

Table 1. Phytosociological parameters of weed plants prior to installation of the experiment in 2018. Manaus, AM.

Class [1]	Family	Scientific Names	TNI	RFr	RDe	RAb	IVI
M	Poaceae	*Axonopus affinis*	414	23.97	43.04	17.80	84.81
M	Poaceae	*Paspalum multicaule*	293	20.55	30.46	14.70	65.70
D	Fabaceae	*Mimosa pudica*	129	23.97	13.41	5.55	42.93
M	Cyperaceae	*Cyperus rotundus*	31	1.37	3.22	23.33	27.92
M	Cyperaceae	*Cyperus diffusus*	27	2.74	2.81	10.16	15.70
M	Commelinaceae	*Commelina erecta*	17	2.74	1.77	6.40	10.90
M	Poaceae	*Paspalum virgatum*	12	1.37	1.25	9.03	11.65
D	Fabaceae	*Pueraria phaseoloides*	12	8.22	1.25	1.50	10.97
D	Rubiaceae	*Spermacoce verticillata*	16	4.11	1.66	4.01	9.79
M	Poaceae	*Eleusine indica*	4	1.37	0.42	3.01	4.80
D	Amaranthaceae	*Alternanthera tenella*	2	2.74	0.21	0.75	3.70
M	Poaceae	*Homolepis aturensis*	1	1.37	0.10	0.75	2.23
D	Solanaceae	*Solanum stramoniifolium.*	1	1.37	0.10	0.75	2.23
D	Euphorbiaceae	*Croton glandulosus*	1	1.37	0.10	0.75	2.23
D	Verbenaceae	*Stachytarpheta cayennensis*	1	1.37	0.10	0.75	2.23
D	Verbenaceae	*Lantana camara*	1	1.37	0.10	0.75	2.23
		Total	962	100.00	100.00	100.00	300.00

[1] M = monocotyledons; D = dicotyledons; TNI = total number of individuals; RFr = relative frequency; RDe = relative density; RAb = relative abundance; IVI = importance value index.

Weed plants were not found in the herbicide-treated area, differently from the treatment using mechanical control, where the presence of some weed species was recorded, although there was a reduction of 80% in the total number of individuals compared with the treatment with no weed control.

Among the cover crops, *B. ruziziensis* was the one that exhibited the smallest number of weed species (4). This cover crop also reduced the total number of individuals by nearly 75% when compared to the treatment with no control, mainly due to its rapid establishment and because it grows in clumps, which increases its competitive ability. These results are in agreement with those found by Soares et al. [3] and Da Gama et al. [18], where this species exhibited excellent soil coverage and good weed suppression, with potential for use as cover crops in the Amazon region.

Regarding *C. ensiformis*, this cover crop exhibited the greatest number of weed species (10), probably due to the upright, determined, and initially slow growth of this legume, which may have favored the emergence of new weed species [25]. Yet, it provided a 29% reduction in the total number of weeds, an intermediate percentage between that found for *B. ruziziensis* and *M. pruriens*.

Mucuna pruriens was the cover crop with the lowest reduction of the total number of individuals (12%) compared with the treatment with no weed control, which may be due to the climbing growth habit of this species, allowing more space available in the soil for weed germination and development [3].

In the phytosociological survey conducted in the total area, prior to the installation of the second experiment, 924 individuals distributed in 19 species were found, 9 monocotyledons and 10 dicotyledons. The Poaceae family was the most abundant, with five species, followed by the Cyperaceae and Euphorbiaceae families, each one with three species (Table 3).

Table 2. Phytosociological parameters of weed plants in a cassava crop grown with different weed management systems in 2019. Manaus, AM.

Treatments	Scientific Names	TNI [1]	RFr	RDe	RAb	IVI
Chemical control	No weed found	0	0	0	0	0
	Total	0	0	0	0	0
Mechanical control	*Mimosa pudica*	10	25.00	34.48	34.48	93.97
	Croton glandulosus	7	18.75	24.14	24.14	67.03
	Alternanthera tenella	6	25.00	20.69	20.69	66.38
	Axonopus affinis	4	18.75	13.79	13.79	46.34
	Acalypha arvensis	2	12.50	6.90	6.90	26.29
Total		29	100.00	100.00	100.00	300.00
No weed control	*Paspalum multicaule*	93	17.65	66.43	68.74	152.81
	Croton glandulosus	20	29.41	14.29	8.87	52.57
	Mimosa pudica	18	29.41	12.86	7.98	50.25
	Acalypha arvensis	5	11.76	3.57	5.54	20.88
	Cyperus distants	3	5.88	2.14	6.65	14.68
	Euphorbia heterophylla	1	5.88	0.71	2.22	8.81
Total		140	100.00	100.00	100.00	300.00
B. ruziziensis	*Croton glandulosus*	15	33.33	45.45	40.00	118.79
	Mimosa pudica	12	33.33	36.36	32.00	101.70
	Axonopus affinis	5	22.22	15.15	20.00	57.37
	Homolepis aturensis	1	11.11	3.03	8.00	22.14
Total		33	100.00	100.00	100.00	300.00
M. pruriens	*Paspalum multicaule*	32	5.00	26.23	45.55	76.78
	Mimosa pudica	36	30.00	29.51	8.54	68.05
	Homolepis aturensis	17	10.00	13.93	12.10	36.03
	Croton glandulosus	13	20.00	10.66	4.63	35.28
	Axonopus affinis	8	5.00	6.56	11.39	22.95
	Rhynchospora nervosa	7	5.00	5.74	9.96	20.70
	Acalypha arvensis	4	10.00	3.28	2.85	16.13
	Cyperus distants	3	10.00	2.46	2.14	14.59
	Pueraria phaseoloides	2	5.00	1.64	2.85	9.49
Total		122	100.00	100.00	100.00	300.00
C. ensiformis	*Homolepis aturensis*	30	6.67	30.30	36.81	73.78
	Cyperus distants	15	6.67	15.15	18.40	40.22
	Croton glandulosus	9	20.00	9.09	3.68	32.77
	Paspalum multicaule	11	6.67	11.11	13.50	31.27
	Mimosa pudica	9	13.33	9.09	5.52	27.95
	Axonopus affinis	8	13.33	8.08	4.91	26.32
	Rhynchospora nervosa	8	6.67	8.08	9.82	24.56
	Alternanthera tenella	6	13.33	6.06	3.68	23.07
	Spermacoce verticillata	2	6.67	2.02	2.45	11.14
	Acalypha arvensis	1	6.67	1.01	1.23	8.90
Total		99	100.00	100.00	100.00	300.00

[1] TNI = total number of individuals; RFr = relative frequency; RDe = relative density; RAb = relative abundance; IVI = importance value index.

Table 3. Phytosociological parameters of weed species before installation of the experiment in 2019. Manaus, AM.

Class [1]	Family	Scientific Names	TNI	RFr	RDe	RAb	IVI
D	Fabaceae	*Mimosa pudica*	404	17.67	43.72	19.49	80.89
M	Poaceae	*Axonopus affinis*	130	8.84	14.07	12.54	35.45
D	Verbenaceae	*Stachytarpheta cayennensis*	102	14.42	11.04	6.03	31.49
M	Poaceae	*Paspalum multicaule*	73	4.65	7.90	13.38	25.93
M	Cyperaceae	*Rhynchospora nervosa*	35	10.70	3.79	2.79	17.28
D	Euphorbiaceae	*Croton lobatus*	32	7.44	3.46	3.67	14.57
D	Rubiaceae	*Spermacoce verticillata*	32	3.72	3.46	7.33	14.52
D	Fabaceae	*Pueraria phaseoloides*	20	8.37	2.16	2.04	12.57
D	Euphorbiaceae	*Acalypha arvensis*	24	3.72	2.60	5.50	11.82
M	Poaceae	*Homolepis aturensis*	21	4.65	2.27	3.85	10.77
M	Poaceae	*Eleusine indica*	15	2.79	1.62	4.58	9.00
M	Poaceae	*Paspalum virgatum*	15	2.79	1.62	4.58	9.00
M	Cyperaceae	*Cyperus rotundus*	5	0.93	0.54	4.58	6.05
M	Cyperaceae	*Cyperus diffusus*	4	0.93	0.43	3.67	5.03
M	Commelinaceae	*Commelina erecta*	4	1.86	0.43	1.83	4.13
D	Amaranthaceae	*Alternanthera tenella*	3	1.86	0.32	1.37	3.56
D	Euphorbiaceae	*Croton glandulosus*	2	1.86	0.22	0.92	2.99
D	Violaceae	*Hybanthus calceolaria*	2	1.86	0.22	0.92	2.99
D	Verbenaceae	*Lantana camara*	1	0.93	0.11	0.92	1.96
		Total	924	100.000	100.000	100.000	300.000

[1] M = monocotyledons; D = dicotyledons; TNI = total number of individuals; RFr = relative frequency; RDe = relative density; RAb = relative abundance; IVI = importance value index.

Differently from what was found in the first year, there was predominance of dicotyledonous individuals in the second year (67.32%), mainly due to the great number of *M. pudica* individuals, which corresponded to approximately 44% of the individuals identified in this survey.

Despite the changes in the floristic composition of the weeding community, most of the individuals identified before the installation of the second experiment had already been recorded in the weed survey conducted in the first year. Among the five weed species with the highest IVI in the surveys carried out before installation of the experiments in both years were *M. pudica*, *A. affinis*, and *P. multicaule*.

Mimosa pudica stands out from the other species for being the one with the highest IVI in the second year (80.89). It is a perennial, herbaceous, or slightly woody, thorny weed plant, with sensitive leaves, prostrate growth habit and propagation by seeds [26]. It is considered a very rustic plant, with good development in soils with low nutrient availability, producing seeds that are capable of germinating under water and saline stress conditions, being indicated for recovery of degraded areas [27].

The mechanical control of this species is difficult because of the thorns and woody roots and also because of the high seed production. Many seeds can remain in the seedbanks in the soil and cause long periods of reinfestation. Because it is very common in the Amazon region, *M. pudica* was already found in diverse studies on weed plants in regional cultivated areas, such as those by Dos Santos [21], Alves Albuquerque et al. [28], and Albertino et al. [23], and has already been considered one of the most important weeds in cassava crop fields [22] and cowpea cultivation [29].

Similar to the first year of the experiment, there were changes in the floristic composition of the weeding community at the end of the second year. However, *M. pudica* was the most important species, both in the first survey and in the final one, considering the highest values found for all parameters assessed (Table 4).

Table 4. Phytosociological parameters of weed plants in a cassava crop grown with different weed management systems in 2020. Manaus, AM.

Treatments	Scientific Names	TNI [1]	RFr	RDe	Rab	IVI
Chemical control	No weed found	0	0	0	0	0
	Total	0	0	0	0	0
Mechanical control	*Mimosa pudica*	9	44.44	47.37	36.00	127.81
	Croton lobatus	6	33.33	31.58	32.00	96.91
	Axonopus affinis	4	22.22	21.05	32.00	75.27
Total		19	100.00	100.00	100.00	300.00
No weed control	*Mimosa pudica*	123	25.00	54.42	36.57	116.00
	Croton glandulosus	39	20.83	17.26	13.92	52.01
	Paspalum multicaule	25	8.33	11.06	22.30	41.70
	Croton lobatus	12	12.50	5.31	7.14	24.95
	Lantana camara	9	16.67	3.98	4.01	24.66
	Pueraria phaseoloides	12	8.33	5.31	10.70	24.35
	Axonopus affinis	6	8.33	2.65	5.35	16.34
Total		226	100.00	100.00	100.00	300.00
B. ruziziensis	*Mimosa pudica*	85	33.33	84.16	79.44	196.93
	Croton glandulosus	10	33.33	9.90	9.35	52.58
	Croton lobatus	3	16.67	2.97	5.61	25.24
	Axonopus affinis	3	16.67	2.97	5.61	25.24
Total		101	100.00	100.00	100.00	300.00
M. pruriens	*Mimosa pudica*	106	31.58	72.11	56.38	160.07
	Paspalum multicaule	20	15.79	13.61	21.28	50.67
	Croton glandulosus	14	21.05	9.52	11.17	41.75
	Croton lobatus	3	15.79	2.04	3.19	21.02
	Lantana camara	3	10.53	2.04	4.79	17.35
	Pueraria phaseoloides	1	5.26	0.68	3.19	9.13
Total		147	100.00	100.00	100.00	300.00
C. ensiformis	*Mimosa pudica*	61	30.77	67.03	45.86	143.67
	Croton glandulosus	12	23.08	13.19	12.03	48.29
	Paspalum multicaule	6	7.69	6.59	18.05	32.33
	Lantana camara	6	15.38	6.59	9.02	31.00
	Croton lobatus	4	7.69	4.40	12.03	24.12
	Axonopus affinis	2	15.38	2.20	3.01	20.59
Total		91	100.00	100.00	100.00	300.00

[1] TNI = total number of individuals; RFr = relative frequency; Rde = relative density; Rab = relative abundance; IVI = importance value index.

Concerning the population dynamics of the weed plants, the main differences observed were in terms of the number of species and total number of individuals, and it was not possible to identify control patterns among the weed species and the assessed treatments, with predominance of some species in most treatments, especially *M. pudica*, *P. multicaule*, and *C. glandulosus*.

For the total number of individuals in the second year, the cover crops with *B. ruziziensis*, *C. ensiformis*, and *M. pruriens* provided reductions of 55, 60, and 35%, respectively, when compared with the treatment with no weed control. With respect to the quantity of weed species, *B. ruziziensis* was again the cover crop with the lowest quantity (4), which underlines its competitive ability.

The variations observed in the weed species and in the phytosociological parameters assessed in the surveys conducted at the beginning and end of this study corroborate the understanding of the floristic composition of the weed plants as a natural dynamic, fluid process, where agricultural practices, soil management system, and the cultural practices adopted can promote significant changes [30].

In general, the weed species identified in the present surveys were recorded in other studies and are commonly found in the Amazon region and are well adapted to the regional conditions. From this perspective, more in-depth studies on the ecology and behavior of these species with respect to different methods of control are necessary for the development of sustainable control strategies.

3.2. Cassava Yield

The summary of variance of the yield components of cassava intercropping with different cover crops is shown in Table 5. Regarding the weed management practice, there was significance for root fresh matter, root dry matter, and shoot dry matter, and no difference for plant height and diameter of the stem base.

Table 5. Summary of the analysis of variance of yield components of cassava culture in cassava production system with different weed management practices in 2018/2019 and 2019/2020 seasons. Manaus, AM.

SV	DF	Means Squares				
		RFM [1]	RDM	SDM	PH	SBD
Block	3	0.466 ^{ns}	0.068 ^{ns}	0.052 ^{ns}	116.8 ^{ns}	52.311 *
Management	5	2.915 *	0.428 *	0.242 *	1224.5 ^{ns}	5.660 ^{ns}
Year	1	0.075 ^{ns}	0.456 *	0.023 ^{ns}	3316.7 *	59.608 *
Man × year	5	0.020 ^{ns}	0.017 ^{ns}	0.006 ^{ns}	251.1 ^{ns}	5.814 ^{ns}
Residual	33	0.180	0.053	0.020	536.2	12.561
Total	47	-	-		-	-

[1] RFM = Root fresh matter; RDM = Root dry matter; SDM = Shoot dry matter; PH = Plant height; and SBD = Stem base diameter; * = Significant difference; and ^{ns} = not significant at the 5% probability level, F-test.

With respect to yield, the treatment with chemical control achieved the best results (29.23 t ha^{-1}), followed by mechanical control (21.79 t ha^{-1}) and *B. ruzizienis* (17.60 t ha^{-1}) and *C. ensiformis* (15.47 t ha^{-1}) cover crops. The lowest yields were observed in the treatments with *M. pruriens* (13.77 t ha^{-1}) and with no weed control (13.60 t ha^{-1}) (Table 6).

Table 6. Cassava yield components in cassava production system with different management practices in 2018/2019 and 2019/2020 growing seasons. Manaus, AM.

Treatments	RFM [1]	RDM	SDM
	-------------------------	t ha^{-1} -------------------------	
No weed control	13.60 c	7.99 c	6.93 b
Mechanical control	21.79 b	11.84 ab	8.95 b
Chemical control	29.23 a	13.60 a	11.51 a
B. ruziziensis	17.60 bc	9.78 bc	7.30 b
C. ensiformis	15.47 bc	9.86 bc	7.55 b
M. pruriens	13.77 c	7.48 c	7.30 b
CV (%)	22.85	22.87	17.48
Growing season 2017/2018	18.97 ^{ns}	9.12 a	8.03 ^{ns}
Growing season 2018/2019	18.18 ^{ns}	11.06 b	8.48 ^{ns}

[1] RFM = Root fresh matter; RDM = Root dry matter; SDM = Shoot dry matter. Means followed by same letter in column and ^{ns} do not differ statistically from each other by the Tukey test ($p < 0.05$).

Although cassava is recognized as rustic plant, fresh root yield was severely affected by weed interference. The treatment with no weed control exhibited more than 50% yield loss compared with the treatment with chemical control, which shows the importance of weed management in cassava yield. Fontes et al. [31] studied the periods of interference of weeds with cassava cultivar *Manteiga* and found that the coexistence of the culture with weeds throughout the crop cycle reduced yields by 96%. According to these authors, this cultivar has low competitive ability against weeds in Amazonas dry land.

The treatment with chemical weed control showed the highest values of yield, root dry matter and shoot dry matter values, probably due to the formation of a uniform straw bed on the soil surface after herbicide application, which may have worked as a physical barrier, helping to keep water in the soil and preventing the emergence of new weeds. The hand-hoeing weed treatment may have suffered the effects of the weed interference found in the treatment, as well as of lower water availability due to the greater soil exposure, which favors water loss to the atmosphere. Although the hoeing treatment achieved lower yields compared with the chemical control, both treatments did not show differences with respect to root dry matter.

In this regard, other studies evaluating weed control in cassava crop fields recorded higher yields in treatments with herbicide applications, compared with treatments using hand weed control [32,33]. Different results were found by Fontes et al. [17], who did not observe differences in cassava cultivar Manteiga yields with herbicide and hand weeding treatments.

With respect to the cover crops, *B. ruziziensis* and *C. ensiformis* showed a moderate degree of interference with cassava, providing yield values similar to the ones achieved with the mechanical control due to the growth habit of these plants, which is compatible with the culture, and reduced quantity of weed species, resulting in less interference when compared with the treatment with no weed control. It should be emphasized that future studies evaluating planting time, density, spacing, and adequate intercropping time, can contribute to raise cassava yields and reduce the potential of weed interference on this crop.

Mucuna pruriens did not show differences from the treatment with no weed control for any of the assessed parameters, indicating intercropping incompatibility with cassava, mainly as a function of its climbing growth habit. However, as it is a rustic legume and of rapid establishment, it has potential for use as green manure or mulch, if cultivated in an area not intercropped with cassava, or even in rotation with this culture.

According to Madembo et al. [34], although intercropped systems with cover crops may reduce crop yields, the use of these plants can be a viable alternative, especially for small farmers, being necessary to investigate crop arrangements capable of increasing the weed suppression potential and reduce interference with the culture.

Despite the importance of optimal production rates, the stability, sustainability of crops, producers' health, preservation, and maintenance of the Amazon ecosystem are factors that must be considered when choosing the best weed management system. It is worth noting that a sustainable production system, when properly employed, adds value to the end product, and can even compensate for any yield losses.

3.3. Soil Chemical Properties

With respect to the chemical properties of soil, despite the variations observed in the two growing seasons, higher pH, K, Ca, Mg, and organic matter contents were found for the cover crops compared to the chemical and mechanical control treatments (Table 7).

The favorable pH value for growing cassava in the North region of Brazil ranges from 5.5 to 7, and 6.5 is the ideal pH [35]. The cover crops contributed to raise the pH value, being closer to the ideal pH for the culture, in comparison to the chemical and mechanical treatments. The effects of the cover crops on the soil pH values are still not fully understood, and contradictory findings are reported in the literature, sometimes with higher values, sometimes with lower values [36,37]. Such variations seem to be mainly related to the biochemical compositions of the cover crops, the soil characteristics, the environmental conditions, and the type of management used.

Regarding organic matter, the cover crops achieved higher values compared to chemical and mechanical weed controls. Higher concentrations of organic matter in soil when using cover crops have been mainly attributed to the incorporation of plant residues, the reduction of the mineralization rate by adopting conservative practices, and less loss of organic matter caused by erosion [38,39]. According to Oliveira et al. [40], agricultural crops that do not use conservation practices tend to reduce the contents of organic matter in soil, especially in the topsoil. Low contents of organic matter tend to diminish the availability of nutrients, such as K, Ca, and Mg, causing more dependence on chemical fertilizers [41,42].

Table 7. Soil chemical properties in the 0 to 20 cm layer, in a cassava production system with different weed management practices in 2018/2019 and 2019/2020. Manaus, AM.

Treatments	pH [1]	OM	P	K	Ca	Mg	Zn	H + Al
	H_2O	dag/kg	mg/dm^3		cmol$_c$/dm^3		mg/dm^3	cmol$_c$/dm^3
				2018/2019				
Mechanical control	5.62 c	3.52 c	3.10 ab	22.75 c	1.88 c	1.18 d	0.65 ^{ns}	4.37 bc
No weed control	5.82 b	3.69 bc	3.45 ab	27.00 b	2.25 b	1.50 ab	0.75 ^{ns}	4.53 bc
B. ruziziensis	6.20 a	3.86 ab	2.92 b	35.75 a	2.56 a	1.52 a	0.75 ^{ns}	4.20 c
C. ensiformis	5.80 bc	3.86 ab	3.97 ab	23.50 c	2.10 b	1.4 bc	0.72 ^{ns}	4.86 b
M. pruriens	5.82 b	4.06 a	3.27 ab	29.25 b	2.07 bc	1.32 bc	0.75 ^{ns}	5.52 a
Chemical control	5.67 bc	3.56 c	4.25 a	22.75 c	1.88 c	1.36 c	0.67 ^{ns}	4.62 bc
CV (%)	1.46	2.86	15.75	4.19	4.30	3.62	13.07	6.11
				2019/2020				
Mechanical control	5.20 c	3.86 c	3.80 ab	24.25 d	1.04 d	0.46 d	0.70 bc	7.34 a
No weed control	5.30 c	4.19 ab	2.45 c	27.50 c	1.19 c	0.47 c	0.72 bc	6.51 ab
B. ruziziensis	5.50 b	4.39 a	3.37 b	30.75 a	1.37 b	0.61 bc	0.95 a	6.60 ab
C. ensiformis	5.82 a	4.23 a	3.57 ab	29.00 b	1.56 a	0.69 a	0.60 c	6.43 b
M. pruriens	5.60 b	4.16 ab	3.42 ab	30.50 a	1.18 c	0.64 b	0.82 ab	7.43 a
Chemical control	5.32 c	3.93 bc	4.10 a	24.25 d	1.06 d	0.47 d	0.75 b	6.93 ab
CV (%)	1.28	2.89	7.95	2.34	2.60	2.75	7.86	5.28

[1] pH = Power of hydrogen; OM = Organic matter; P = Phosphorus; K = Potassium; Ca = Calcium; Mg = Magnesium; Zn = Zinc; and H + Al = Potential acidity. Means followed by same letter in column and ^{ns} do not differ statistically from each other by the Tukey test ($p < 0.05$).

In the first year, *B. ruziziensis* was the species that exhibited the highest contents of K, Ca, Mg, and organic matter and the lowest potential acidity. Because it is a species that produces great amount of biomass, with capacity to uptake nutrients from the deepest layers in soil [43], the cutting and rapid degradation of vegetable residues that this species has have contributed to the improved level of chemical properties observed in the upper layers of soil. Similar results were found by Ensinas et al. [44], who studied the effects of some cover crops on the chemical properties of soil, including *B. ruziziensis*, and found that the cover crops provided improved K and Mg contents. Arf et al. [45] reported that *B. ruziziensis* and *C. ensiformis* provided higher contents of P and K in the soil, and Demir and Işık [37], when they studied the influence of cover crops on the soil quality, observed that the cover crops provided increased K and Mg contents, when compared with the treatments with chemical and mechanical weed control.

It should be noted that *B. ruzizienis* was the cover crop that exhibited the lowest P contents in the soil in the two years assessed. Studies involving brachiaria species and phosphorus availability in the soil reported that, contrary to expectations, *B. ruziziensis* reduced P content in the soil, while exhibiting a higher P concentration in plant tissues [46,47].

The chemical control treatment achieved the best P contents in the soil in both years of assessment. Considering that there was fertilization of soil with this nutrient, following recommendation of Dias et al. [11], it is possible that the higher P contents found in this treatment were due to the absence of weeds or cover crops capable of extracting this nutrient from the soil and better conservation of the soil surface provided by crop residues (straw). According to Magolbo [48], because it participates in the synthesis of starch in the plants, it is expected that P supply in adequate amounts can increase the plant growth and cassava yields. So, greater P contents in soil are highly desirable for cassava, and many studies demonstrate that this is a crop responsive to phosphate fertilization [48–50].

As for Zn contents, no differences were observed between the treatments in the first year, but *B. ruziziensis* and *M. pruriens* exhibited higher contents of this micronutrient in the second year. Due to the variations found, future studies are necessary to assess the real impact of these cover crops on Zn contents in soil, considering that this is an essential micronutrient for plant growth, and its deficiency in soil represents a global concern, especially in tropical soils, being considered the micronutrient that most commonly limits cassava production [51,52].

Finally, although an improvement of the chemical properties of soil is quite desirable, the mere conservation of the parameters initially observed already represents a great advance under the perspective of sustainable cropping systems, considering that conventional cultivation practices, dependent on intense use of fertilizers and pesticides, may cause degradation of the soil properties in the medium and long term.

4. Conclusions

Cover crops changed the floristic composition of the weed community in cassava cultivation, reducing the diversity of species and the quantity of individuals. The weed species reduced cassava yields by more than 50% under the Amazon ecosystem conditions. The cover crops *B. ruziziensis* and *C. ensiformis* increased fresh and dry matter of cassava roots when compared with the treatment with no control. The cover crops increased the pH, OM, K, Ca, and Mg when compared with the treatments with chemical and mechanical weed control.

Brachiaria ruziziensis and *C. ensiformis* are recommended as a cover plants in cassava production systems in the Amazon region. The use of cover crops associated with cassava is a sustainable management option because, in addition to the suppressive effect on weeds, cover crops improve the chemical properties of soil, which may contribute to increasing cassava production in the long term, considering the low natural fertility of the Amazonian soils. Although studies on this theme are still incipient in the Amazon region, the results obtained in this study are useful in the development of strategies for sustainable weed management and improvement of the quality of Amazonian soils.

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