sustainability

MDPI

Article

Short-Term Agronomic and Economic Responses to the Adoption of Cover Crops for Corn Rotation in the Brazilian Semiarid Region

João Henrique Silva da Luz [1,2,*], Matheus Batista da Silva [2], Luana do Nascimento Silva Barbosa [1], José Wilker Germano de Souza [1], Maria Raquel da Silva Farias [1], John Kennedy dos Santos [2], Maria Gleide Jane Lima De Gois [1], Sivaldo Soares Paulino [1], Ricardo Barros Silva [1], Dayane Mércia Ribeiro Silva [1], Deyvison de Asevedo Soares [2], Paulo Sergio Pavinato [2] and Valdevan Rosendo dos Santos [1,*]

[1] Department of Agronomy, Campus Arapiraca, Federal University of Alagoas, Av. Manoel Severino Barbosa Bom Sucesso, Arapiraca 57309-005, Brazil; luana.barbosa@arapiraca.ufal.br (L.d.N.S.B.); wilkergermano99@gmail.com (J.W.G.d.S.); maria.raquel@arapiraca.ufal.br (M.R.d.S.F.); janelima813@gmail.com (M.G.J.L.D.G.); sivaldo.paulino@arapiraca.ufal.br (S.S.P.); ricardoufal2010@gmail.com (R.B.S.); dayannemercia@hotmail.com (D.M.R.S.)

[2] Department of Soil Science, "Luiz de Queiroz" College of Agriculture, University of Sao Paulo, Piracicaba 13418-900, Brazil; matheus.silvaal@usp.br (M.B.d.S.); john.kennedy@usp.br (J.K.d.S.); deyvison.a.soares@gmail.com (D.d.A.S.); pavinato@usp.br (P.S.P.)

* Correspondence: jhluz@usp.br or agrojluz@gmail.com (J.H.S.d.L.); valdevan@arapiraca.ufal.br (V.R.d.S.)

Citation: Luz, J.H.S.d.; Silva, M.B.d.; Barbosa, L.d.N.S.; Souza, J.W.G.d.; Farias, M.R.d.S.; Santos, J.K.d.; Gois, M.G.J.L.D.; Paulino, S.S.; Silva, R.B.; Silva, D.M.R.; et al. Short-Term Agronomic and Economic Responses to the Adoption of Cover Crops for Corn Rotation in the Brazilian Semiarid Region. *Sustainability* **2023**, *15*, 15091. https://doi.org/10.3390/su152015091

Academic Editors: Marlene Cristina Alves, Carolina Dos Santos Batista Bonini and Luis Eduardo Akiyoshi Sanches Suzuki

Received: 29 July 2023
Revised: 7 September 2023
Accepted: 9 September 2023
Published: 20 October 2023

Abstract: Cover crops (CCs) have demonstrated their significance in enhancing the agronomic and economic performance of corn in succession. In this paper, we assess the agronomic responses and short-term economic returns of adopting cover crops (CCs) for corn cultivation in the sandy soils of the semiarid region of northeast Brazil, with the aim of addressing the additional challenges of CCs adoption in semiarid regions. The field study was conducted in Arapiraca, Alagoas, under no-tillage conditions for two cropping seasons. A randomized complete block design was employed, comprising six CCs (sunn hemp, spectabilis, jack bean, pigeon pea, lab lab, and millet) treatments and one fallow, with 18 replications. The CCs were cultivated for 60 days before corn planting. Drip irrigation was applied during the grain-filling stage of corn growth. Over the two cropping seasons, the biomass and nutrient cycling of the CCs, corn yield, and economic returns were determined, as well as the total organic carbon (TOC) and Mehlich-1 extractable P levels in the soil after corn harvest. The grain yields with sunn hemp, spectabilis, and jack bean were superior (~10%) to that of the fallow (7.7 vs. 7.1 Mg ha^{-1}), irrespective of the cropping season. Sunn hemp exhibited a higher biomass accumulation and ensured greater nutrient cycling, except for K, while lab lab and millet displayed a similar potential, although substantial variations were observed between seasons. Under sunn hemp and jack bean, the TOC increased by ~9%, particularly in the second season. Regarding the available P, spectabilis and jack bean exhibited the highest levels, with an increase of ~74% compared to the fallow (~31.1 vs. 17.9 mg dm^{-3}). Spectabilis and lab lab demonstrated more promising results, both agronomically and economically. However, millet and sunn hemp have the potential to reduce costs over multiple cropping seasons. Therefore, the adoption of cover crops is a sustainable and economically viable agricultural practice. However, it is essential to acknowledge that our results do not represent rainfed conditions and require further investigation.

Keywords: net returns; nutrients cycling; sunn hemp; spectabilis; jack bean; pigeon pea; lab lab; millet; land equivalent ratio; corn yield stability

1. Introduction

Modern agriculture faces significant challenges in ensuring global food security and the sustainability of production systems. Increasing plant diversity is a fundamental strategy to optimize crop efficiency [1], promote yield stability, and mitigate the negative impacts of monoculture practices [2]. The adoption of cover crops (CCs), with their distinct characteristics and multiple benefits [2,3], has emerged as a promising approach to enhancing corn yields in semiarid regions [4,5].

CCs, when strategically incorporated into the cropping system, can suppress weeds, increase the total organic carbon (TOC) in the soil, reduce nitrate leaching [6,7], and improve soil structure [8,9], consequently mitigating erosion and maintaining soil moisture [10]. CCs, especially legumes due to their nitrogen-fixing ability, play a crucial role in enhancing nutrient cycling, particularly for highly mobile soil nutrients (e.g., K^+ and NO_3^-) [2,3,11] and less available nutrients (e.g., P) [12–16]. The decomposition of residual biomass increases nutrient availability (e.g., P [17]) synchronously with the demand for cash crops [2,3,11,18].

Despite the evident benefits of CCs, their implementation in semiarid regions presents challenges and has associated drawbacks [3,5]. In these areas, limited water availability, due to irregular rainfall patterns and high temperatures, can hinder the effectiveness of this practice [19,20]. Water competition and nutrient immobilization between CCs and cash crops [5] may lead to reduced corn yields [20], jeopardizing the economic viability of cultivation [4,21]. Corn plays a critical role in the food chain in this region, making sustainable and adapted agricultural practices essential to ensure both food and economic security.

Therefore, understanding the nutrient cycling potential, management practices, and the types of CC species that are most adaptable is essential for recommending the adoption of CCs in agricultural production systems in semi-arid regions [5,22]. In this context, our study focuses on investigating the interaction between CCs and corn rotation in the semiarid region of northeast Brazil. Our objective was to evaluate the agronomic responses and short-term economic returns (over two cropping seasons) of adopting CCs for corn rotation in the sandy soils of the semiarid region of northeast Brazil.

2. Materials and Methods

2.1. Study Area and Experimental Design

This study was conducted over two successive cropping seasons (2021 and 2022) in a field trial in the experimental area of the Federal University of Alagoas, Campus Arapiraca (9°42′00″ S, 36°41′12″ W), situated at an altitude of 324 m (Figure 1). The region is a tropical 'As' climate according to the Köppen classification, with a well-defined rainy season (April–September) followed by a dry season (October–March). The average annual precipitation is approximately 850 mm, and the mean air temperature is 25 °C. Precipitation data for the experimental period and the regional climatological pattern are presented in Figure 2.

The experimental site's soil was classified as Argissolo Vermelho-Amarelo Distrófico by the Brazilian committee [23], which is equivalent to Acrisols (IUSS Working Group, [24]) or Ultisols (Soil Survey Staff [25]), with a sandy loam texture. Before being cultivated, the area remained fallow for approximately 10 years until 2009. After this year, it was always cultivated with CCs, vegetables, or fodder with low nutrient inputs. Corn cultivation was initiated for the first time in 2021, marking the first cropping season of this study. The soil's chemical and textural properties before the experiment's implementation are presented in Table 1.

The experimental design adopted was a randomized complete block design with 18 replications. The treatments comprised six CC species (sunn hemp (*Crotalaria juncea*), spectabilis (*Crotalaria spectabilis*), jack bean (*Canavalia ensiformis*), pigeon pea (*Cajanus cajan*), lab lab (*Dolichos lab lab*), and millet (*Pennisetum glaucum*)), and a fallow plot. For the fallow plot, frequent manual weed control took place. Each plot size was 8 × 5 m (40 m^2). The CCs were manually sown in the second half of April 2021 and 2022, with row spacing of 25 cm for the millet and 50 cm for the other CCs.

For the establishment of the CCs, 44 kg ha^{-1} of phosphorus (P) was applied via a single superphosphate (8.3% soluble P) in broadcast without incorporation in 2021. In 2022, P fertilization was applied to the corn. The seeding rates were 30 kg ha^{-1} for sunn hemp, 15 kg ha^{-1} for spectabilis, 100 kg ha^{-1} for jack bean, 25 kg ha^{-1} for millet, and 40 kg ha^{-1} for pigeon pea and lab lab. During the CCs growth stage, no fertilizers or agricultural pesticides were applied, and weed control was carried out manually.

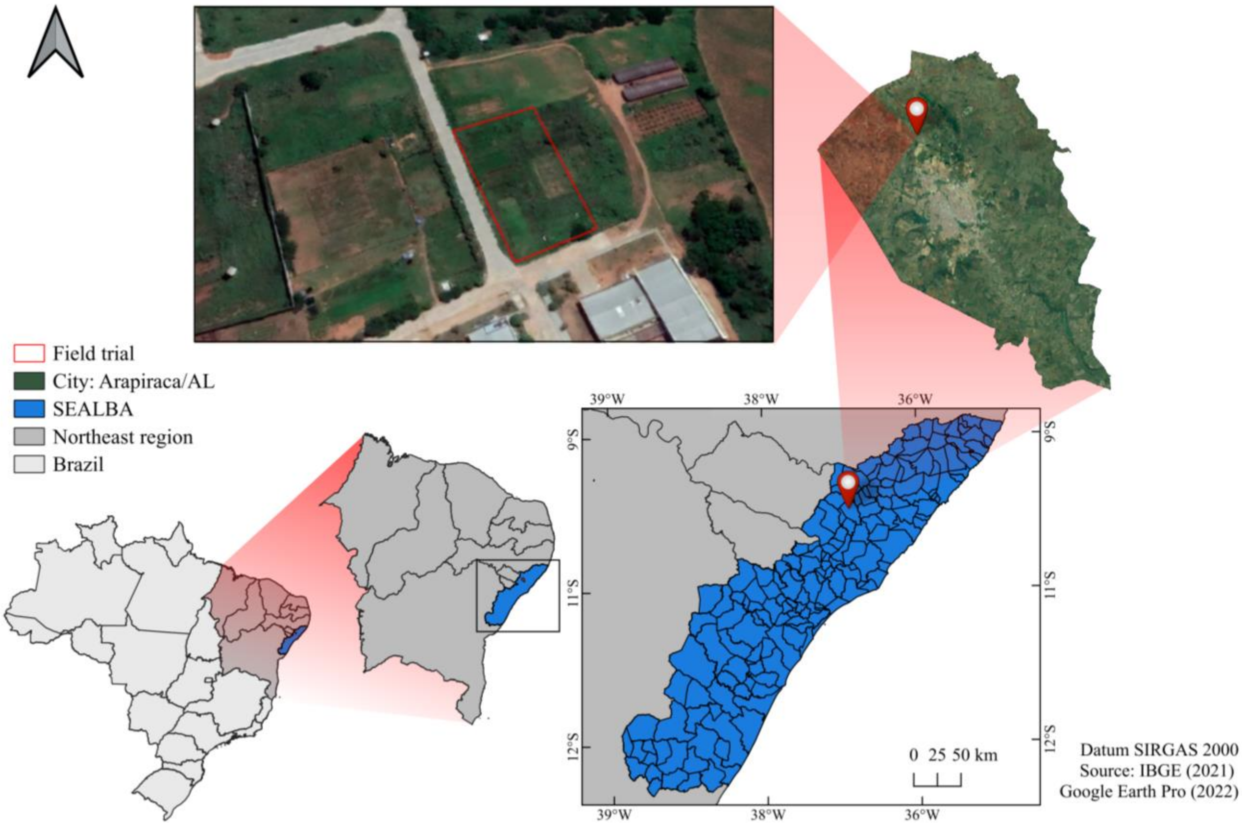

Figure 1. Schematic map of the northeastern region of Brazil, with an emphasis on the agricultural region called SEALBA, and the location of the field trial with cover crops and corn in Arapiraca-AL, Brazil.

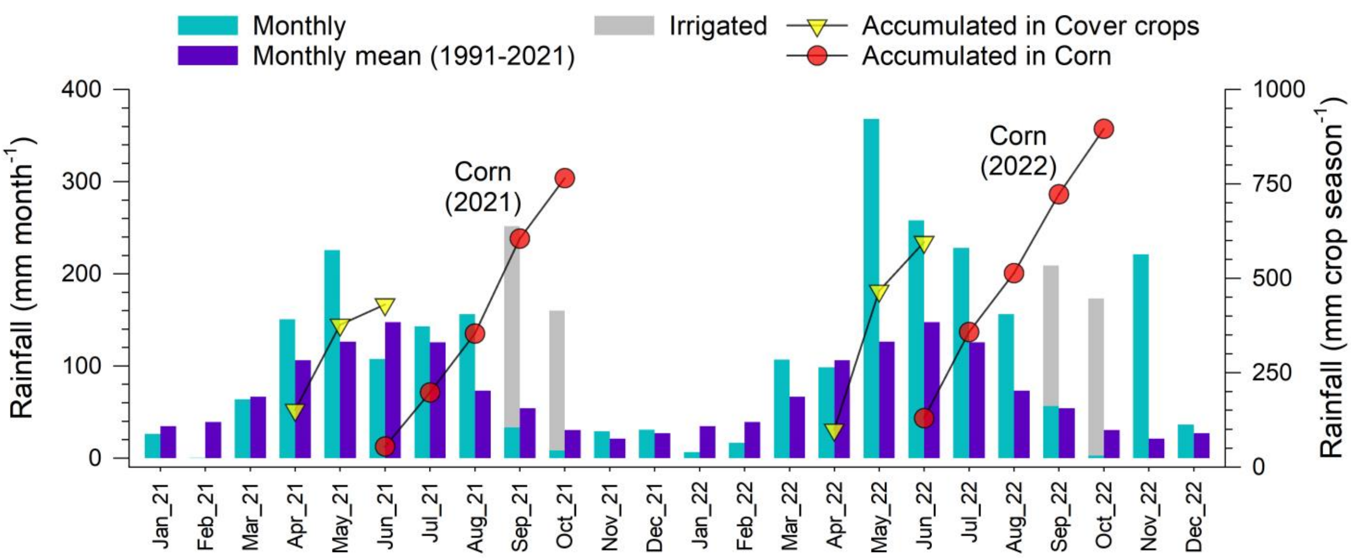

Figure 2. Monthly rainfall during the experimental period (2021–2022), and the climatological normal (1991–2021) of monthly precipitation, accumulated precipitation, and supplementary irrigation for the growing seasons of cover crops and corn, Arapiraca, AL, Brazil.

Table 1. Chemical and textural properties of the soil at depths of 0–10 and 10–20 cm before the experiment's establishment.

Prof. (cm)	pH (H_2O)	TOC (g dm^{-3})	Al^{3+}	H + Al	Ca^{2+}	Mg^{2+}	K^+	P-M-1 (mg dm^{-3})	CEC	BS	Sand	Silt	Clay
			cmolc dm^{-3}						pH 7	(%)	g kg^{-1} | (0–20 cm)		
0–10	6.5	12.5	0	1.8	1.8	1.35	0.27	19.5	5.36	66.6	720	124	156
10–20	6.4	6.51	0	2.2	1.8	1.05	0.19	16.5	5.33	58.4			

TOC: total organic carbon; P-M-1: available P using Mehlich-1 extractor; CEC: cation exchange capacity; BS: base saturation.

After 60 days of CCs cultivation (in the second half of June), the CCs were desiccated using glyphosate (N-(phosphonomethyl) glycine) (1.7 g i.a. ha^{-1}). Subsequently, the hybrid corn (BM 990©) was mechanically sown with a density of ~75,000 plants ha^{-1} directly over the CCs. The row spacing was 80 cm, and there was 17 cm between the plants, with 30 kg ha^{-1} of nitrogen (N) applied via ammonium sulfate (21% N and 22% S) in the planting rows. The first topdressing application for the corn occurred at the V4 stage, with 70 kg ha^{-1} of N (via urea, 46% N) and 20 kg ha^{-1} of K (via KCl, 58% K). The second topdressing was applied at the V7-8 stage with 50 kg ha^{-1} of N (via ammonium sulfate). The cultural practices for weed, pest, and disease management were carried out following regional recommendations for corn crops. In summary, we applied glyphosate (1.7 g a.i. ha^{-1}) at the V4 stage for weed control, and thiamethoxam (56 g a.i. ha^{-1}) and lambda-cyhalothrin (43 g a.i. ha^{-1}), split into two applications at the V6 and VT stages, for the control of sucking insects. The same approach was used for the application of azoxystrobin (86 g a.i. ha^{-1}) and cyproconazole (48 g a.i. ha^{-1}) for the control of phytopathogenic fungi.

To mitigate the water deficit at the end of the corn cycle, supplemental irrigation was provided using a drip irrigation system. Irrigation management was based on the drainage of five lysimeters in the plot of each CC to determine and meet the crops' evapotranspiration demands. Irrigation was applied, with a total of 370 mm of water in 2021, while in 2022 it was 322 mm.

2.2. Agronomic Evaluations

2.2.1. Plant Evaluations and Nutrient Uptake

We evaluated the dry mass (DM, kg ha^{-1}) of the CCs (one day before desiccation) by collecting two random 1 m2 subsamples per plot. Subsequently, the samples were air-dried and then oven-dried at 60 °C until a constant weight. The DM was ground to a 2 mm mesh using a Wiley mill for subsequent leaf nutrient analysis. The leaf nutrient content was analyzed through nitroperchloric acid digestion for P, K, Mg, and S, and through sulfuric acid digestion for N, following Tedesco et al. [26]. The K and Mg content were determined using flame spectrometry, while P was analyzed using the ammonium molybdate colorimetric method in a spectrophotometer at 880 nm, and S was determined using turbidimetry. Due to the frequent weed control in the fallow plot, there was a high variation in the DM ($<0.2 \pm 0.2$ t ha^{-1}), which is why we did not conduct nutrient content analyses for this treatment.

The corn grain yield (kg ha^{-1}) was assessed by manually harvesting the three central rows (excluding 0.5 m from each plot's ends), and the grain moisture was adjusted to 13%. The yield stability was calculated based on the coefficient of variation (CV%) using the mean and standard deviation of the treatments in each cropping season. Additionally, the change in yield (see Supplementary Data) and the land equivalent ratio (LER) [27,28] were calculated using Equation (1).

$$\mathrm{LER} = \frac{\text{Yield CCs}}{\text{Yield fallow}} \tag{1}$$

The LER expresses how much fallow land is required to achieve the same yield obtained with CCs. A LER < 1.0 indicates a negative effect on yield with the use of CCs, while a LER > 1.0 indicates a positive effect on yield, thus representing land savings with CCs.

2.2.2. Soil Analysis

After the corn was harvested, soil sampling was carried out with three subsamples to form a composite sample per plot at two depths (0–10 cm and 10–20 cm). The soil samples were air-dried, sieved through a 2 mm mesh, and analyzed for available P (mg dm^{-3}) and total organic carbon (TOC, g dm^{-3}).

The available P in the soil was quantified using the Mehlich-1 method, following Teixeira et al. [28]. A total of 5 g of soil and 50 mL of Mehlich-1 extractor solution (50 mM HCl + 12.5 mM H_2SO_4) were used. The samples were agitated for 5 min on a horizontal shaker at 200 rpm and decanted for 16 h. The P content in the extracts was determined using the molybdate blue method. A TOC analysis was conducted using 510 ± 10 mg of soil, applying the wet oxidation method with potassium dichromate, and titrating with ammonium ferrous sulfate [28].

2.3. Economic Analysis

The economic responses of CCs adoption vs. fallow were determined in terms of gross revenues, total costs, total profit, and net returns (provided in USD ha^{-1}) for each cropping season (2021 and 2022). The model developed by the Brazilian Institute of Agricultural Economics [29] was employed for the economic analysis. In our survey, the total cost for corn with supplemental irrigation in Arapiraca-AL was USD 643.78 ha^{-1} in 2021 and USD 1132.18 ha^{-1} in 2022, according to data from the Brazilian National Supply Company (Companhia Nacional de Abastecimento Brasileira-CONAB) and regional agricultural companies. The additional cost for the CCs seeds in 2021 was USD 86.4 ha^{-1} for sunn hemp, USD 38.0 ha^{-1} for spectabilis, USD 200.4 ha^{-1} for jack bean, USD 94.2 ha^{-1} for pigeon pea, USD 25.2 ha^{-1} for lab lab, and USD 9.9 ha^{-1} for millet. In 2022, all the CCs seed costs increased by ~50%, similar to production costs, due to exchange rate and commodity fluctuations caused by the uncertainties of the SARS-CoV-2 (COVID-19) pandemic.

The selling price of a bag (60 kg) of corn was USD 16.84 sc^{-1} in January 2021 and USD 14.74 sc^{-1} in the same month in 2022. The exchange rate of the dollar at the time of sale in 2021 (USD1 = BRL 5.713) was higher than in 2022 (USD 1 = BRL 5.318), as reported by the Central Bank of Brazil. The net returns were calculated as the difference between the profitability of the CCs and fallow.

2.4. Data Analysis

The normality (Shapiro–Wilk test) and variance homogeneity (Bartlett test) were assessed for all the variables, and when the assumptions were not met, the data were transformed using the Anderson-Darling method. The results were analyzed through ANOVA ($p \leq 0.05$), with a joint analysis applied to measure the responses between cropping seasons. The CCs means were compared using the Scott-Knott method ($p \leq 0.05$), and the responses between cropping seasons were measured using the *t*-test ($p \leq 0.05$). We applied a clustered heatmap analysis to measure the variation/correlation between the variables and treatments. Here, we used values close to zero for the variables that were not determined during the fallow period to enable this analysis. Statistical analyses and heatmaps were using R® software version 4.3.1 with the "easyanova" and "pheatmap" packages. Boxplot or bar graphs were generated using SigmaPlot® version 12.5.

3. Results

3.1. Grain Yield and Production Stability

The grain yield of corn did not show a significant interaction between the years and cover crops (p = 0.176, Figure 3A). Overall, the yields were higher in 2021 (~8 Mg ha^{-1}), representing a 12% increase when compared to 2022 (~7.1 Mg ha^{-1}). Concerning the cover crops, sunn hemp, spectabilis, and jack bean had statistically similar means in both

2021 and 2022, with an average yield of ~7.7 Mg ha^{-1}. These cover crops all outperformed the fallow with an effect size corresponding to a 20% change in yield (Figure S3B) in 2022; however, it was almost negligible in 2021 (~1.1%). As for pigeon pea, lab lab, and millet, their yield was ~7.4 Mg ha^{-1} in both cropping seasons.

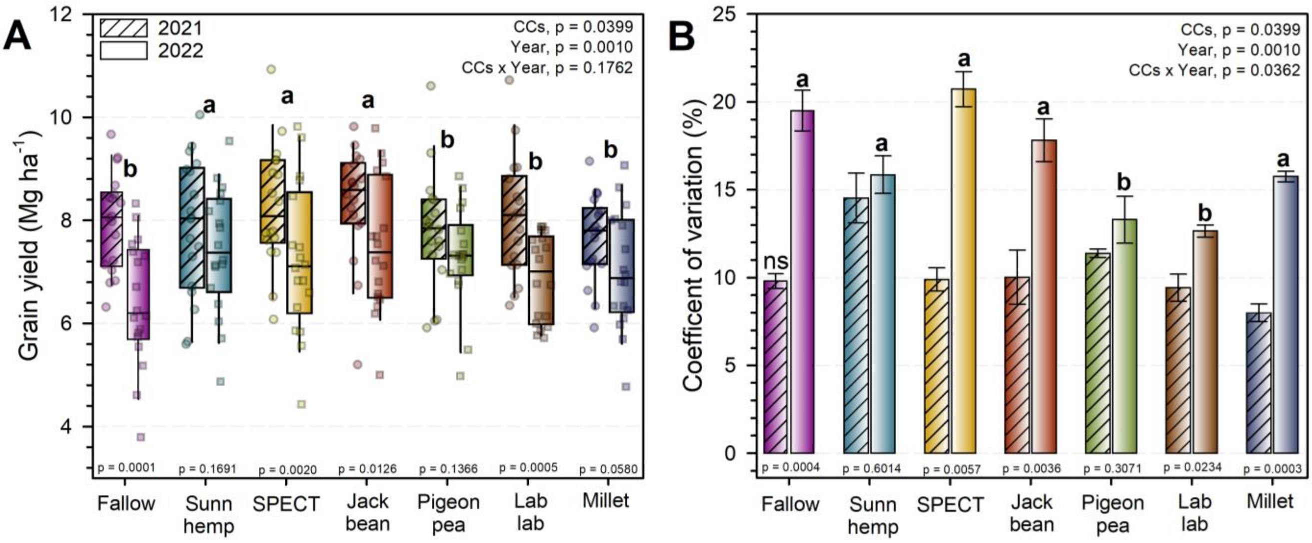

Figure 3. Grain yield (**A**) and yield stability (**B**) for two crops with cover crops in sandy soil in a semiarid region in Brazil. SPECT: spectabilis; CCs: cover crops. Means followed by the same letters between CCs did not differ using the Scott-Knott test ($p \leq 0.05$). A p-value close to the X-axis indicates a response between years. ns: not significant using an F-test ($p > 0.05$).

The yield stability (CV%, Figure 3B) was mainly influenced by the cropping season, with a value of ~10.4% in 2021 and ~16.5% in 2022. In 2022, the cover crops demonstrated significant differences compared to the fallow. Both pigeon pea and lab lab significantly reduced the variation in corn yield compared to the fallow, with reductions of >13% for both, while the fallow exhibited a variation of 19.5%. It is worth noting that the 2022 cropping season was atypical for the region (Figure 2), with precipitation 82% above the climatological normal. Therefore, the cover crops played a crucial role in maintaining yield and production stability during this exceptional year.

3.2. Biomass and Nutrient Uptake by Cover Crops

In both cropping seasons, the cover crops showed significant effects on the dry matter (DM) and nutrient uptake of N, P, and K (Figure 4, $p < 0.05$). Sunn hemp (~4 Mg ha^{-1}) and millet (3 Mg ha^{-1}) exhibited the highest amounts of dry matter among the cover crops (Figure 4A), regardless of the cropping season ($p > 0.05$). On the other hand, pigeon pea showed the lowest DM performance, accumulating ~1.2 Mg ha^{-1}, independent of the season ($p = 0.58$).

Sunn hemp and pigeon pea stood out in both cropping seasons, with the highest and lowest values of dry matter and nutrient uptake (Figure 4, $p < 0.05$). Sunn hemp showed the highest N uptake, with ~112 kg ha^{-1}, representing an increase of 82–125% compared to the other cover crops (Figure 4B), irrespective of the season ($p > 0.05$). Following in sequence were jack bean and lab lab, with 70 kg ha^{-1} of N uptake. Pigeon pea had the lowest performance, with ~37 kg ha^{-1} of N uptake, regardless of the season ($p = 0.44$).

The P uptake by the cover crops was influenced by the species and cropping season ($p < 0.001$). In the first season (2021), millet showed the highest P uptake (16.3 kg ha^{-1}), followed by lab lab and sunn hemp, with values close to ~9.6 kg ha^{-1}, while the other cover crops had a P uptake of <6.6 kg ha^{-1}. In the second season (2022), sunn hemp and spectabilis absorbed more P than the other species (~22.1 kg ha^{-1}), representing an increase of ~36% compared to millet (Figure 4C). Interestingly, sunn hemp, spectabilis, and jack bean were the only cover crops that showed a response between cropping seasons, with an increase of 60, 68, and 69%, respectively, between 2021 and 2022. These cover crops are not highly demanding of the available P [13], but they can respond to its increased availability. The initial P content was classified as moderate (18.5 mg kg^{-1}) for the sandy soil with a low P adsorption, and the addition of 44 kg ha^{-1} in maize increased the soil's P availability (Figure 5B). Thus, the responses between the crops in the different seasons indicates that these plants are responsive to an increase in the available P or to exploring the legacy P in the soil (Figure 5B–D, with a significant increase in leaf P content (Figure S1B).

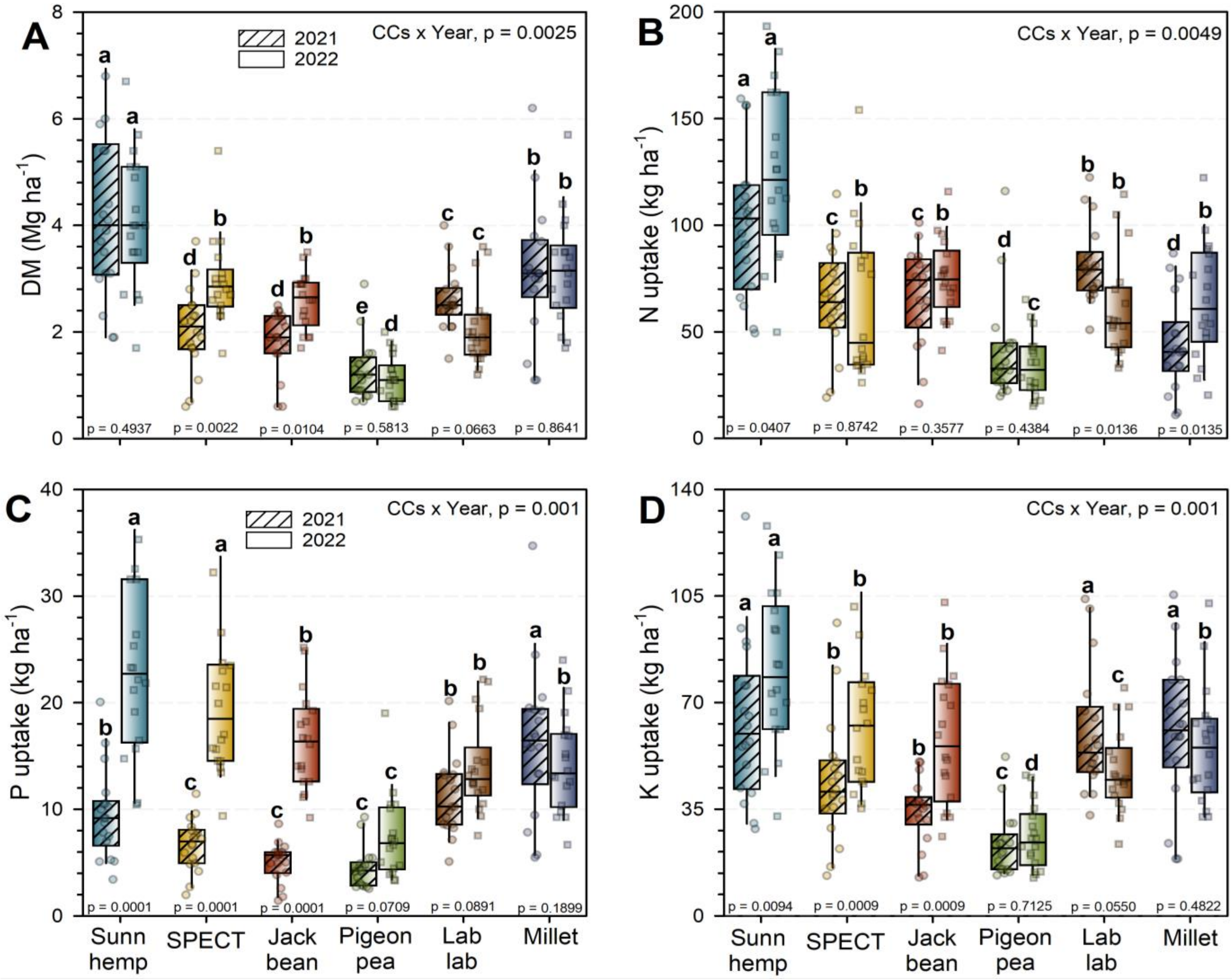

Figure 4. Dry mass (**A**) and N, P, and K uptake (**B**–**D**) by cover crops for two crops in sandy soil in a semiarid region in Brazil. SPECT: spectabilis; CCs: cover crops. Means followed by the same letters between CCs did not differ using the Scott-Knott test ($p \leq 0.05$). A *p*-value close to the *X*-axis indicates a response between years. ns: not significant using an F-test ($p > 0.05$).

Similar responses were observed for K uptake as for P, with an interaction between the cover crops and cropping seasons ($p < 0.001$), although with a smaller effect between the seasons. In 2021, sunn hemp, millet, and lab lab were similar to each other, all outperforming the other species, with uptakes of 63.7, 60.3, and 59.7 kg ha^{-1}, respectively. In the second season, sunn hemp absorbed more K (80.4 kg ha^{-1}) than the other plants, being superior to spectabilis, jack bean, and millet (~55.4 kg ha^{-1}) by 31% (Figure 4D). As with P uptake, only sunn hemp, spectabilis, and jack bean showed significant differences between the cropping seasons (due to leaf K content, Figure S1C), with increases of 21, 33, and 41%, respectively, between 2021 and 2022.

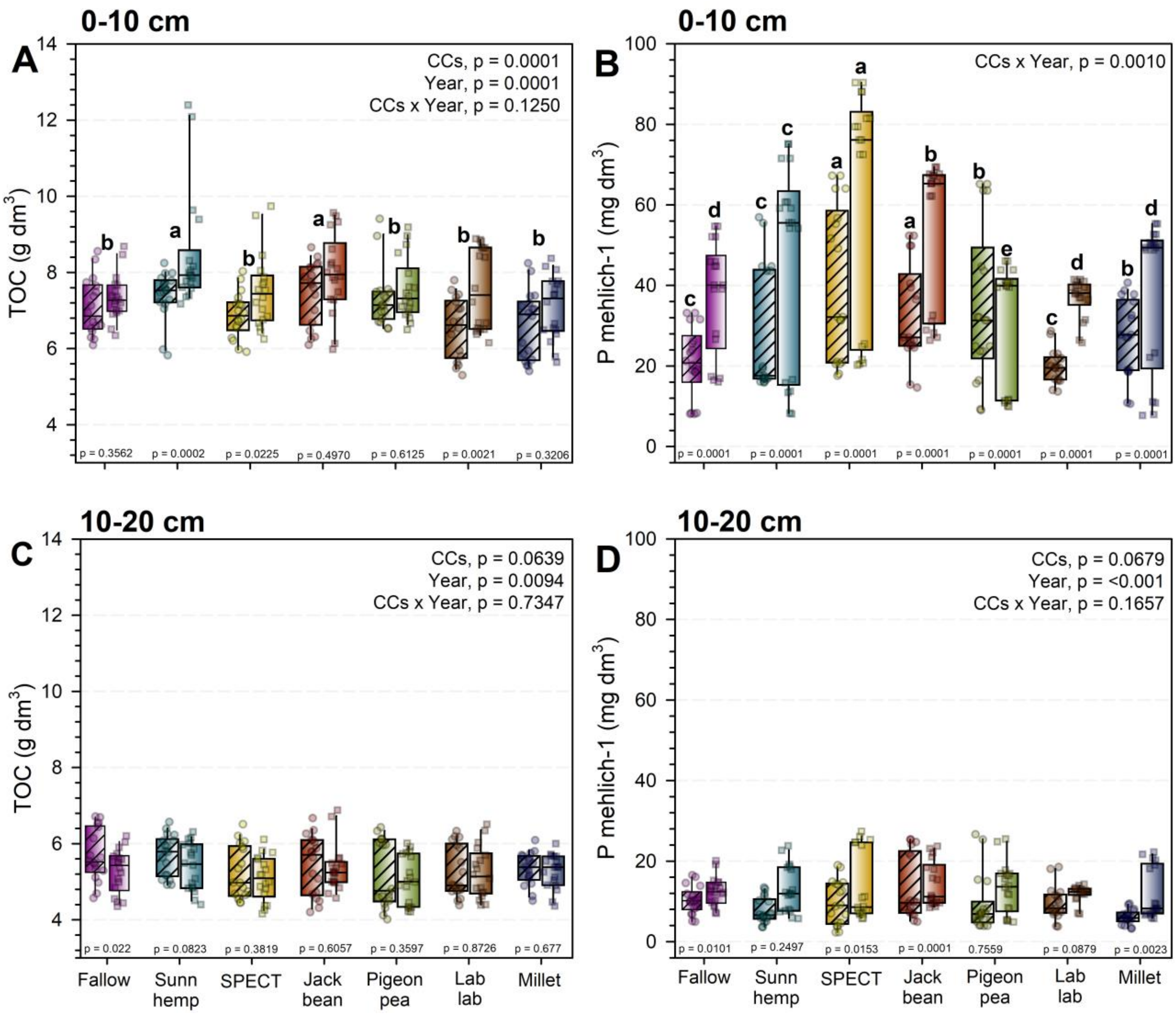

Figure 5. Total organic carbon (**A**,**C**) and available P content (**B**,**D**) at two depths (0–10 and 10–20 cm) of two crops with cover crops in sandy soil in a semiarid region in Brazil. SPECT: spectabilis; CCs: cover crops. Means followed by the same letters between CCs did not differ using the Scott-Knott test ($p \leq 0.05$). A *p*-value close to the *X*-axis indicates a response between years. ns: not significant using an F-test ($p > 0.05$).

3.3. Total Organic Carbon and P Available in the Soil

There were responses in the soil's chemical attributes to the cover crops, with a simple effect on the TOC and an interaction ($p = 0.0001$) with the available soil's P at a 0–10 cm depth (Figure 5). At a 0-10 cm depth, the highest TOC levels occurred for sunn hemp and jack bean (~7.9 g kg^{-1}, $p = 0.0001$), exceeding the other treatments, with an average increase of ~8.8% compared to the fallow (7.2 g kg^{-1}). In general, the TOC increased by 6.5% from 2021 to 2022 ($p = 0.00001$).

Regarding the available P levels, strong variations were observed between the cropping seasons ($p = 0.0001$, Figure 5B–D) only at the first depth (0–10 cm). In 2021, spectabilis and jack bean showed the highest P levels, with an increase of 74% when compared to the fallow (~31.1 vs. 17.9 mg dm^{-3}), while lab lab and sunn hemp did not differ from the fallow. In the 2022 cropping season, spectabilis and jack bean also exhibited the highest levels, with averages of 39.2 and 30.4%, respectively, compared to the fallow. On the other hand, millet and lab lab did not differ significantly from the fallow. It should be noted that soil sampling occurred after the corn harvest, i.e., the available P that was depleted to meet the crop demand may have been replenished by the cover crop residues during decomposition [13,17].

3.4. Profitability

The results for the economic return (net return) were strongly influenced by the cropping season (p = 0.0001), with a lesser magnitude of effect for the cover crops (p = 0.018). Overall, in 2021, there was a loss of USD -60 ha^{-1}, which is different from 2022, when there was an economic return of USD +60 ha^{-1} (Figure 6A). The average profitability of corn was higher in 2021 (USD ~1256 ha^{-1}) compared to 2022 (USD ~724 ha^{-1}) (Figure S3A), although the greatest response in yield occurred in 2022 (~20%, Figure S3B).

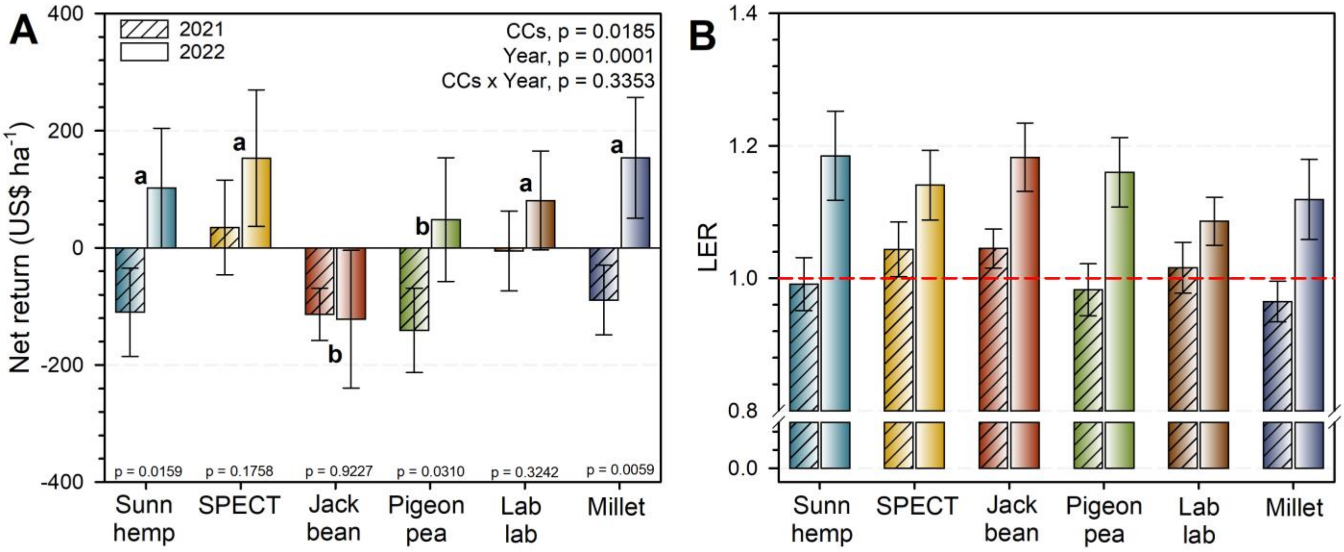

Figure 6. Net return (**A**) and land equivalent ratio (LER, (**B**)) for two crops with cover crops in sandy soil in a semiarid region of Brazil. Means above the red line indicate a positive response, while those below it indicates negative responses. SPECT: spectabilis; CCs: cover crops. Means followed by the same letters between CCs did not differ using the Scott-Knott test ($p \leq 0.05$). A p-value close to the X-axis indicates a response between years. ns: not significant using an F-test ($p > 0.05$).

Among the cover crops, spectabilis was the most promising in terms of economic return (USD +94 ha^{-1}), although it did not statistically differ from lab lab, millet, or sunn hemp (with USD +38, +32, and -4 ha^{-1}, respectively). Jack bean was the only one that showed a negative response in both cropping seasons (USD -118 ha^{-1}, p = 0.9927), and it did not differ from pigeon pea (Figure 6A).

For the land equivalent ratio (LER), a variable that measures land economy, there was no response in 2021. However, in 2022, all the cover crops showed responses > 1, especially for sunn hemp and jack bean (Figure 6B).

A hierarchical clustering separated the four major groups of treatments with a high similarity (Y-axis of the heatmap, Figure 7). This approach clearly distinguished the fallow from the cover crops in both cropping seasons, mainly due to low nutrient cycling, yield, and profitability (this statement may be biased due to our lack of nutrient cycling measurements in the fallow). Another strong cluster occurred with spectabilis, millet, sunn hemp, and jack bean in the 2022 cropping season, due to higher nutrient cycling and, mainly, higher economic return, LER, change in yield, available P, leaf P content, and P uptake by the cover crops. We expected the same species to cluster together between the seasons (to evidence consistent results), but this only occurred with pigeon pea, where median responses were obtained for the evaluated characteristics.

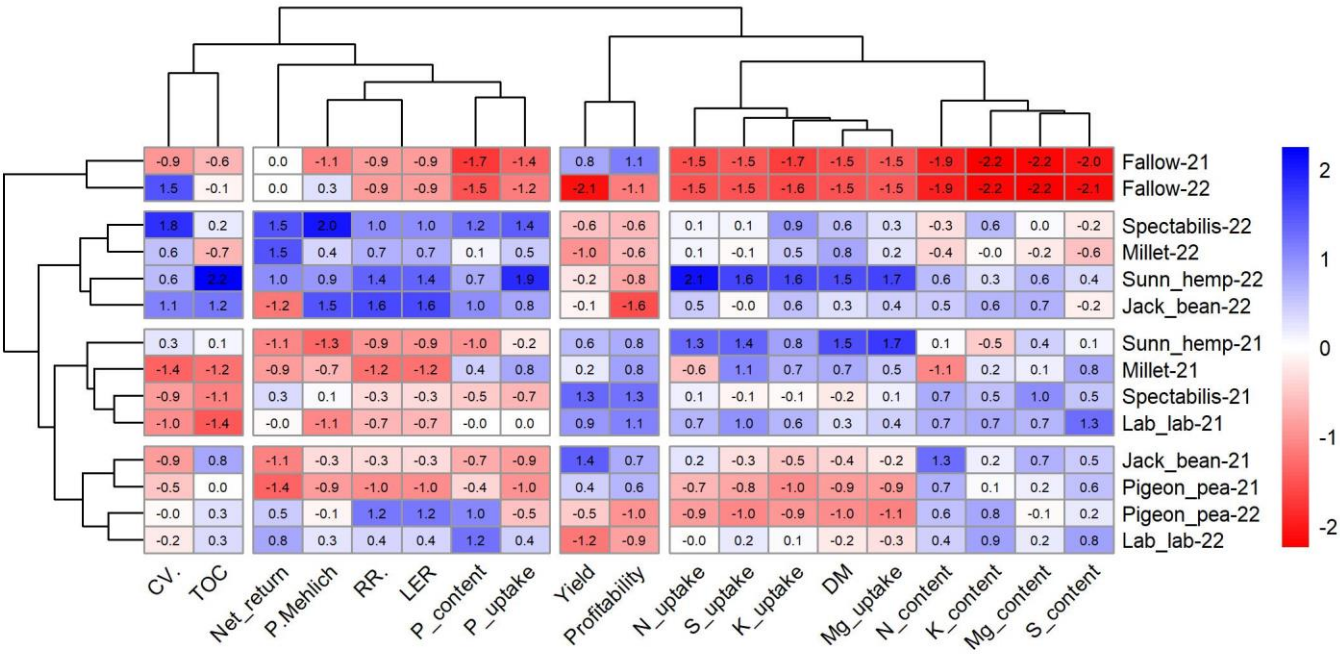

Figure 7. Heatmap clustering using Euclidean distance of CCs responses of corn crops in sandy soil in a semiarid region in Brazil. Note: the color and numbers represent the variation around the overall mean of each variable (by columns). RR: change in yield; CV: coefficient of variation; LER: land equivalent ratios; DM: dry mass of CCs; TOC: total organic carbon.

4. Discussion

Our results demonstrate the potential of adopting CCs to enhance corn cultivation in sandy soils in a semiarid climate. Although the benefits on yield were not significant in the first cropping season, we observed agronomic and economic gains in the second season, suggesting a possible cumulative effect.

4.1. Grain Yield and Production Stability

The CCs increased corn yield by ~20% compared to that of the fallow in 2022 (7.98–6.40 Mg ha^{-1}). The fallow condition exposes the soil to adverse edaphoclimatic conditions, leading to nutrient leaching, increased soil temperature due to direct solar radiation, and higher evapotranspiration [5]. In contrast, the CCs protect and accumulate biomass on the soil surface, retaining moisture and making nutrients (e.g., N, K, and P) available, which are essential for corn yield and quality [11]. Similar results regarding the effect of CCs on subsequent crop yield were reported by Zhao et al. [1]. The authors observed positive (73.6%), neutral (0.7%), and negative (27.7%) effects on corn yield after growing legumes like crotalarias, lab lab, and pigeon pea.

One reason for the efficiency of legumes lies in their ability to establish symbiotic relationships with diazotrophic bacteria, which provide atmospheric N to the system through biological nitrogen fixation [3]. Additionally, CCs with low water availability (<500 mm) cover the soil surface, reducing erosion and evapotranspiration rates [5,30].

Previous research evaluating nine CCs, including sunn hemp, pigeon pea, and millet, by Carvalho et al. [31], also observed positive effects on corn yield and stability. The authors attributed their results to the higher dry matter accumulation and synchronized residue decomposition of corn phenology. However, our study differs from Carvalho et al.'s [31], as we cut the CCs prematurely (60 days after sowing) due to low water availability during the intercropping period, and to avoid exceeding the ideal corn-sowing window.

Corn yield can be influenced by precipitation, temperature, planting density, early desiccation, and CCs' lignin content [31]. Legumes with lower C:N ratios can explain the increased corn yield, as their residue decomposition requires the microbial immobilization of

N as a catalytic process. This lower C:N ratio reduces N competition with the cash crop and maximizes nutrient mineralization, aligning with corn's nutritional requirements [3,5,22]. The split N fertilization during corn cultivation may have favored this process for millet, the only species with a high C:N ratio in this study.

4.2. Biomass and Nutrient Uptake by Cover Crops

Sunn hemp and millet consistently showed the highest dry matter production and N, P, and K uptake, in both cropping seasons (Figure 4). High dry matter production is essential when selecting CC species for agricultural systems [3]. Crop residue controls weeds, improves nutrient cycling [32], increases TOC (Figure 5A–D) [6,7,9] and soil restructuring [8,9], and protects against erosion [10]. However, it can compete with cash crops for water, light, and nutrient immobilization, even in temporal cropping systems, which may reduce the cash crops yield [3].

Furthermore, legume CCs are often used as natural organic fertilizers due to their N inputs to the system through biological nitrogen fixation, which is linearly related to crop growth and soil N levels [33]. A split-cover fertilizer N application is carried out to improve corn yield, and CCs can enhance it as green manure [34]. This benefit is crucial for reducing mineral input, consequently reducing the risk of economic losses, soil, and agroecosystem pollution [35].

Previous studies in semiarid regions [36,37] have reported that sunn hemp reached flowering within 60–65 days after sowing. Scavo et al. [3] confirmed this as the ideal termination period for CCs, since the plants achieve the highest dry matter and leaf nutrient accumulation at this time. This justifies our results, as the CCs were grown for only 60 days, and only sunn hemp, spectabilis, and millet flowered. Santos et al. [36], under similar conditions to our study, reported that sunn hemp had the highest growth rate and the shortest time to flowering (60 days). The authors evaluated species similar to our study; spectabilis, pigeon pea, lab lab, and jack bean took 78, 89, 89, and 83 days to reach flowering, respectively. This suggests that greater benefits may be observed in management that allows CCs cultivation for more than 60 days before corn cultivation.

Our results showed the high P-cycling capacity of the CCs (up to 35 kg ha^{-1}). This could contribute to synchronized nutrition with corn's demand, as soluble and inorganic P contained in the residues of cytoplasm and vacuoles are released within a few days, while insoluble, organic P compounds are released more slowly and need to be mineralized for plant uptake [17]. P uptake is influenced by the area around the explored by roots, due to its low mobility in the soil; millet showed higher P uptake in 2021, surpassing the other species, possibly due to its higher root density. Parvin et al. [19] reported a root density of 4 g cm^2 in millet, superior to that of sunn hemp and lab lab (2–3 and 1–2 g cm^2, respectively).

In 2022, all the legume CCs showed an increased P uptake compared to 2021, especially sunn hemp (60%). Similar results were obtained by Rigon et al. [38] in their study of crop rotation and residue quality affecting P dynamics in tropical soils. The authors observed a 13% increase in the available P in the soil after growing sunn hemp, indicating its high capacity to explore for P. The increases in 2022 may be related to mineral P input, as the environment became richer in P compared to the previous cropping season. The increase in the leaf P content of the CCs (Figure S2B) suggests that these legumes are responsive to the soil's available P. Legumes may possess physiological and morphological adaptations in their roots that maximize P acquisition from soil pools of P [15]. Several studies have shown that P uptake is strongly correlated with root exudate release, influencing P solubilization and mineralization, and consequently increasing the available P, especially in P-deficient soils [13,16,39].

Regarding K cycling, deep-rooted plants like millet exploit the leached K and enrich the superficial depths during early residue decomposition [18]. It has been reported that lab lab may have a higher root density than sunn hemp [19]; thus, we expected higher K uptake due to its preferential flow. However, sunn hemp showed a higher K uptake than the other species in 2021. This was attributed to sunn hemp's adaptability to the region's edaphoclimatic conditions [36], rapid growth, and no N limitations due to biological fixation [40]. These characteristics allowed the species to reach the reproductive stage before 60 days, a phase when higher K demand occurs for flowering and grain filling [41].

4.3. Total Organic Carbon and P Available in the Soil

Our results showed a significant increase in the TOC promoted by the CCs, with rapid responses in the superficial depth (0–10 cm), similar to the findings of Veloso et al. [42]. The authors reported that differences in TOC increments can occur between the surface and deeper soil depths. A recent meta-analysis by Vendig et al. [6] also reported similar effects in 59.7% of 434 observations of CCs associated with commercial crops. They further described the direct consequences of increased TOC on grain yield, soil quality, and fertility. Peng et al. [7] demonstrated that CCs are crucial for improving soil health indicators, with more C stored and sequestered in the soil.

TOC increase results from sunn hemp adoption, similar to those of our study, were reported by Ferreira et al. [43]. Positive results for legumes, especially in comparison to the fallow, were also reported by Marcelo et al. [44]. Collier et al. [45] reported that sunn hemp promoted a higher TOC content compared to jack bean in corn intercropping, emphasizing the importance of the species used.

The increase in available P in the short-term using CCs compared to the fallow varied among species, mainly at a 0–10 cm depth (Figure 5B–D). This can be explained with respect to P input by broadcast application (mainly for the responses between years) and low mobility in the soil profile [46]. Furthermore, it is the zone of greatest root exploration and microbial activity, which are responsible for the decomposition of residual biomass and soil P transformations [13,46]. These results are similar to those of Hansen et al. [47], who reported that covering arable areas with plant residues can contribute to soil P availability. CCs promote soil exploration through their roots, enabling various forms of P solubilization, especially in soils with low availability [14,16,38]. These plants are efficient in extracting and utilizing soil P, reducing dependence on phosphate fertilizers [12,13]. CCs also influence soil P fractions, increasing the labile organic pool [14,16,38].

4.4. Profitability

Economic returns are a strong incentive for CCs adoption by farmers, as it provides an opportunity to increase profits and yield stability. The selected CC species should not increase the agronomic risks (e.g., allelopathy and reduced water and nutrient availability) that directly affect the cash crop yield, and the cost–benefit should be neutral or preferably positive. Our results indicate that spectabilis and lab lab are the most promising economically in the short term; while millet and sunn hemp had losses in 2021, these were offset by gains in 2022.

Jack bean showed the highest grain yield responses (Figures 3A,6B and S3B), but they were not sufficient to cover costs in both cropping seasons, making it the least-performing CC. This was due to the high sowing rate (100 kg ha^{-1}) and seed cost (USD 200 ha^{-1}) of the species. We emphasize that the SARS-CoV-2 pandemic influenced the economics of both seasons in Brazil, mainly due to currency exchange variations (USD to BRL) and commodity price fluctuations at the time of input purchase and grain sale.

Previous studies have shown that CCs' net return may take a medium-to-long time to be evident [21]. Except when the CCs were harvested for forage sales [4], the practice did not reduce (in the short term) the benefits to soil health or cash crop yield when compared to fallow [48]. Government cost-sharing policies for CCs adoption can facilitate their uptake. This was decisive for CCs adoption in the Corn Belt of the USA [4,21]. DeLaune et al. [21] reported on government funding of USD 114 ha^{-1} for producers to grow CCs in Chillicothe, TX, USA. Programs like this could aid CCs adoption in Brazil, especially in the northeast, as they provide ecosystem services [3,5,22] and strengthen soil health [2,6,7]. However, no similar policies or pilot projects exist in Brazil at the time of this study.

5. Conclusions

The adoption of cover crops has proven to be beneficial for corn yield in sandy soils, but it varies with the species of cover crops cultivated in the Brazilian semiarid region. This can be attributed to increased nutrient cycling, possibly accompanied by synchronized nutrient release with corn's demand, as well as an increase in available P and TOC. Legume species, such as jack bean and pigeon pea, showed the highest yield responses. However, for these species, the economic return was negative in both cropping seasons. Taking into account both agronomic and economic aspects simultaneously, spectabilis and lab lab proved to be more promising. Nevertheless, millet and sunn hemp could offset costs over multiple cropping seasons.

Our findings are relevant for farmers, researchers, and agricultural policymakers seeking effective strategies to optimize agricultural production and improve the sustainability of cropping systems. This practice has the potential to enhance both yields and stability, coupled with reduced fertilizer inputs and increased soil carbon stocks. However, we highlight that further studies should be conducted to investigate the medium- and long-term responses, considering irrigation factors and stable economic scenarios. This will be essential to provide more precise recommendations for cover crops species with the highest potential to benefit producers in semiarid regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152015091/s1, Figure S1: The leaf N, P, K, Mg, and S content of cover crops; Figure S2: The Mg and S uptake by cover crops; Figure S3: The profitability and change in yield of corn.

Author Contributions: Conceptualization, V.R.d.S., J.H.S.d.L., M.B.d.S. and M.G.J.L.D.G.; methodology, J.H.S.d.L., L.d.N.S.B., R.B.S. and V.R.d.S.; software, J.H.S.d.L., M.B.d.S. and J.K.d.S.; validation, J.H.S.d.L., V.R.d.S., D.d.A.S. and M.B.d.S.; formal analysis, J.H.S.d.L., L.d.N.S.B., S.S.P. and J.W.G.d.S.; investigation, all authors; resources, V.R.d.S. and P.S.P.; data curation, J.H.S.d.L., L.d.N.S.B. and M.B.d.S.; writing—original draft preparation, J.H.S.d.L., M.B.d.S., L.d.N.S.B., J.W.G.d.S., M.R.d.S.F., M.G.J.L.D.G. and J.K.d.S.; writing—review and editing, D.M.R.S., R.B.S., S.S.P., P.S.P., D.d.A.S. and J.H.S.d.L.; visualization, J.H.S.d.L., L.d.N.S.B. and M.B.d.S.; supervision, V.R.d.S. and P.S.P.; project administration, V.R.d.S.; funding acquisition, V.R.d.S. and P.S.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Alagoas States Research Foundation (Fundação de Amparo a Pesquisa do Estado de Alagoas—FAPEAL), grant number 60030.0000000467/2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors M.B.d.S., L.d.N.S.B., J.W.G.d.S., M.R.d.S.F. and J.K.d.S. are thankful for the coordination of the Improvement of Higher Education Personnel (CAPES) and the National Council for Scientific and Technological Development for scholarships. J.H.S.d.L. thanks the São Paulo Research Foundation (FAPESP, N°. 2021/08396-7) for scholarships.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhao, J.; Chen, J.; Beillouin, D.; Lambers, H.; Yang, Y.; Smith, P.; Zeng, Z.; Olesen, J.E.; Zang, H. Global Systematic Review with Meta-Analysis Reveals Yield Advantage of Legume-Based Rotations and Its Drivers. *Nat. Commun.* **2022**, *13*, 4926. [CrossRef] [PubMed]
2. Yu, R.-P.; Yang, H.; Xing, Y.; Zhang, W.-P.; Lambers, H.; Li, L.; Yu, R.-P.; Yang, H.; Xing, Y.; Zhang, W.-P.; et al. Belowground Processes and Sustainability in Agroecosystems with Intercropping. *Plant Soil* **2022**, *476*, 263–288. [CrossRef]
3. Scavo, A.; Fontanazza, S.; Restuccia, A.; Pesce, G.R.; Abbate, C.; Mauromicale, G. The Role of Cover Crops in Improving Soil Fertility and Plant Nutritional Status in Temperate Climates. A Review. *Agron. Sustain. Dev.* **2022**, *42*, 93. [CrossRef]

4. Obour, A.K.; Dille, J.; Holman, J.; Simon, L.M.; Sancewich, B.; Kumar, V. Spring-Planted Cover Crop Effects on Weed Suppression, Crop Yield, and Net Returns in No-Tillage Dryland Crop Production. *Crop. Sci.* **2022**, *62*, 1981–1996. [CrossRef]
5. Blanco-Canqui, H.; Ruis, S.J.; Holman, J.D.; Creech, C.F.; Obour, A.K. Can Cover Crops Improve Soil Ecosystem Services in Water-Limited Environments? A Review. *Soil Sci. Soc. Am. J.* **2022**, *86*, 1–18. [CrossRef]
6. Vendig, I.; Guzman, A.; De La Cerda, G.; Esquivel, K.; Mayer, A.C.; Ponisio, L.; Bowles, T.M. Quantifying Direct Yield Benefits of Soil Carbon Increases from Cover Cropping. *Nat. Sustain.* **2023**, *6*, 1125–1134. [CrossRef]
7. Peng, Y.; Rieke, E.L.; Chahal, I.; Norris, C.E.; Janovicek, K.; Mitchell, J.P.; Roozeboom, K.L.; Hayden, Z.D.; Strock, J.S.; Machado, S.; et al. Maximizing Soil Organic Carbon Stocks under Cover Cropping: Insights from Long-Term Agricultural Experiments in North America. *Agric. Ecosyst. Environ.* **2023**, *356*, 108599. [CrossRef]
8. Salomão, P.E.A.; Kriebel, W.; dos Santos, A.A.; Martins, A.C.E. A Importância Do Sistema de Plantio Direto Na Palha Para Reestruturação Do Solo e Restauração Da Matéria Orgânica. *Res. Soc. Dev.* **2020**, *9*, e154911870. [CrossRef]
9. Qi, J.; Jensen, J.L.; Christensen, B.T.; Munkholm, L.J. Soil Structural Stability Following Decades of Straw Incorporation and Use of Ryegrass Cover Crops. *Geoderma* **2022**, *406*, 115463. [CrossRef]
10. Suzuki, L.E.A.S.; Amaral, R.D.L.; Almeida, W.R.d.S.; Ramos, M.F.; Nunes, M.R. Oat Straw Mulching Reduces Interril Erosion and Nutrient Losses Caused by Runoff in a Newly Planted Peach Orchard. *Soil. Syst.* **2023**, *7*, 8. [CrossRef]
11. Piva, J.T.; Bratti, F.; Locatelli, J.L.; Ribeiro, R.H.; Besen, M.R.; Brancaleoni, E.; Schmitt, D.E. Use of Winter Cover Crops Improves Maize Productivity under Reduced Nitrogen Fertilization: A Long-Term Study. *Bragantia* **2021**, *80*, e0621. [CrossRef]
12. Soltangheisi, A.; Teles, A.P.B.; Sartor, L.R.; Pavinato, P.S. Cover Cropping May Alter Legacy Phosphorus Dynamics under Long-Term Fertilizer Addition. *Front. Environ. Sci.* **2020**, *8*, 13. [CrossRef]
13. Hallama, M.; Pekrun, C.; Lambers, H.; Kandeler, E. Hidden Miners—The Roles of Cover Crops and Soil Microorganisms in Phosphorus Cycling through Agroecosystems. *Plant Soil.* **2019**, *434*, 7–45. [CrossRef]
14. Teles, A.P.B.; Rodrigues, M.; Bejarano Herrera, W.F.; Soltangheisi, A.; Sartor, L.R.; Withers, P.J.A.; Pavinato, P.S. Do Cover Crops Change the Lability of Phosphorus in a Clayey Subtropical Soil under Different Phosphate Fertilizers? *Soil Use Manag.* **2017**, *33*, 34–44. [CrossRef]
15. Lazali, M.; Drevon, J.J. Mechanisms and Adaptation Strategies of Tolerance to Phosphorus Deficiency in Legumes. *Commun. Soil Sci. Plant Anal.* **2021**, *52*, 1469–1483. [CrossRef]
16. Lambers, H. Phosphorus Acquisition and Utilization in Plants. *Annu. Rev. Plant Biol.* **2022**, *73*, 17–42. [CrossRef]
17. Damon, P.M.; Bowden, B.; Rose, T.; Rengel, Z. Crop Residue Contributions to Phosphorus Pools in Agricultural Soils: A Review. *Soil Biol. Biochem.* **2014**, *74*, 127–137. [CrossRef]
18. Baptistella, J.L.C.; de Andrade, S.A.L.; Favarin, J.L.; Mazzafera, P. Urochloa in Tropical Agroecosystems. *Front. Sustain. Food Syst.* **2020**, *4*, 119. [CrossRef]
19. Parvin, S.; Condon, J.; Rose, T. Rooting Depth and Water Use of Summer Cover Crops in a Semi-Arid Cropping Environment. *Eur. J. Agron.* **2023**, *147*, 126847. [CrossRef]
20. Jones, C.; Olson-Rutz, K.; Miller, P.; Zabinski, C. Cover Crop Management in Semi-Arid Regions: Effect on Soil and Cash Crop. *Crops Soils* **2020**, *53*, 42–51. [CrossRef]
21. DeLaune, P.B.; Mubvumba, P.; Fan, Y.; Bevers, S. Agronomic and Economic Impacts of Cover Crops in Texas Rolling Plains Cotton. *Agrosyst. Geosci. Environ.* **2020**, *3*, e20027. [CrossRef]
22. Blanco-Canqui, H.; Shaver, T.M.; Lindquist, J.L.; Shapiro, C.A.; Elmore, R.W.; Francis, C.A.; Hergert, G.W. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. *Agron. J.* **2015**, *107*, 2449–2474. [CrossRef]
23. Santos, H.G.; Jacomine, P.K.T.; Anjos, L.H.C. *Sistema Brasileiro de Classificação de Solos*, 5th ed.; Embrapa Solos: Rio de Janeiro, Brazil, 2018; Volume 1, p. 353.
24. FAO. *World Reference Base for Soil Resources 2014, Update 2015 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports: Rome, Italy, 2015.
25. USDA. Soil Survey Staff. In *Soil Taxonomy: A Basic Systems of Soil Classification for Making and Interpreting Soil Surveys*, 12th ed.; USDA (United States Department of Agriculture): Washington, DC, USA, 2017.
26. Tedesco, M.; Gianello, C.; Bissani, C.; Bohnen, H. *Análises de Solo, Plantas e Outros Materiais*, 2nd ed.; Universidade Federal do Rio Grande do Sul: Porto Alegre, Brazil, 1995; Volume 1, p. 174.
27. Hedges, L.V.; Gurevitch, J.; Curtis, P.S. The Meta-analysis of Response Ratios in Experimental Ecology. *Ecology* **1999**, *80*, 1150–1156. [CrossRef]
28. Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. *Manual de Métodos de Análise de Solo*, 3rd ed.; Embrapa Solos: Rio de Janeiro, Brazil, 2017; Volume 1, p. 212. ISBN 9788570357717.
29. Matsunaga, M.; Bemelmans, P.F.; Toledo, P.E.N.; Dulley, R.D.; Okawa, H.; Pedroso, I.A. *Cost of Production Methodology Utilized by the IEA [Institute of Agricultural Economics; Brazil]*; Agricultura em Sao Paulo: Sao Paulo, Brazil, 1976; Volume 1, p. 200.
30. Malone, L.C.; Mourtzinis, S.; Gaska, J.M.; Lauer, J.G.; Ruark, M.D.; Conley, S.P. Cover Crops in a Wisconsin Annual Cropping System: Feasibility and Yield Effects. *Agron. J.* **2022**, *114*, 1052–1067. [CrossRef]
31. Carvalho, A.M.; Coser, T.R.; Rein, T.A.; Dantas, R.A.; Silva, R.R.; Souza, K.W. Manejo de Plantas de Cobertura Na Floração e Na Maturação Fisiológica e Seu Efeito Na Produtividade Do Milho. *Pesqui Agropecu Bras.* **2015**, *50*, 551–561. [CrossRef]

32. De Marques Pires, M.F.; de Souza, H.A.; Medeiros, J.C.; Dalla Rosa, J.; de Souza Martins, R.V.; Sobral, A.H.S.; Pereira Carvalho, S.; de Sousa Vera, G.; de Melo Jorge Vieira, P.F.; Sagrilo, E. Nutrient Uptake by Soybean Plants in Succession of Cover Crops in Northeast of Brazil. *Commun. Soil Sci. Plant Anal.* **2023**, *54*, 945–963. [CrossRef]
33. Hu, A.; Huang, D.; Duan, Q.; Zhou, Y.; Liu, G.; Huan, H. Cover Legumes Promote the Growth of Young Rubber Trees by Increasing Organic Carbon and Organic Nitrogen Content in the Soil. *Ind. Crops Prod.* **2023**, *197*, 116640. [CrossRef]
34. Quinn, D.J.; Poffenbarger, H.J.; Miguez, F.E.; Lee, C.D. Corn Optimum Nitrogen Fertilizer Rate and Application Timing When Following a Rye Cover Crop. *Field Crops Res.* **2023**, *291*, 108794. [CrossRef]
35. Raza, S.; Farmaha, B.S. Contrasting Corn Yield Responses to Nitrogen Fertilization in Southeast Coastal Plain Soils. *Front. Environ. Sci.* **2022**, *10*, 955142. [CrossRef]
36. Dos Santos, V.R.; Costa, L.C.; Rocha, A.M.S.; dos Santos, C.G.; dos Santos, M.A.L.; Rabêlo, F.H.S.; de Prado, R.M. Biomass Accumulation, Extraction and Nutrient Use Efficiency by Cover Crops. *Res. Soc. Dev.* **2020**, *9*, e9969109433. [CrossRef]
37. Cavalcante, V.S.; Santos, V.R.; dos Santos Neto, A.L.; dos Santos, M.A.L.; dos Santos, C.G.; Costa, L.C. Biomassa e Extração de Nutrientes Por Plantas de Cobertura. *Rev. Bras. Eng. Agrícola Ambient.* **2012**, *16*, 521–528. [CrossRef]
38. Rigon, J.P.G.; Crusciol, C.A.C.; Calonego, J.C.; Pavinato, P.S.; Azevedo, A.C.; Rosolem, C.A. Intensive Crop Rotations and Residue Quality Increase Soil Phosphorus Lability under Long-Term No-till in Tropical Soils. *Soil Tillage Res.* **2022**, *223*, 105446. [CrossRef]
39. Zhu, S.G.; Cheng, Z.G.; Wang, J.; Gong, D.S.; Ullah, F.; Tao, H.Y.; Zhu, H.; Duan, H.X.; Yang, Y.M.; Xiong, Y.C. Soil Phosphorus Availability and Utilization Are Mediated by Plant Facilitation via Rhizosphere Interactions in an Intercropping System. *Eur. J. Agron.* **2023**, *142*, 126679. [CrossRef]
40. Eberle, C.; Shortnacy, L. Sunn Hemp Planting Date Effect on Growth, Biomass Accumulation, and Nutritive Value in Southeastern Wyoming. *Crop Sci.* **2021**, *61*, 4447–4457. [CrossRef]
41. Fernández, F.G.; Brouder, S.M.; Volenec, J.J.; Beyrouty, C.A.; Hoyum, R. Root and Shoot Growth, Seed Composition, and Yield Components of No-till Rainfed Soybean under Variable Potassium. *Plant Soil* **2009**, *322*, 125–138. [CrossRef]
42. Veloso, M.G.; Angers, D.A.; Tiecher, T.; Giacomini, S.; Dieckow, J.; Bayer, C. High Carbon Storage in a Previously Degraded Subtropical Soil under No-Tillage with Legume Cover Crops. *Agric. Ecosyst. Environ.* **2018**, *268*, 15–23. [CrossRef]
43. Ferreira, P.A.A.; Ceretta, C.A.; Tiecher, T.; Facco, D.B.; Garlet, L.P.; Soares, C.R.F.S.; Soriani, H.H.; Nicoloso, F.T.; Giachini, A.J.; Brunetto, G.; et al. Rhizophagus Clarus and Phosphorus in Crotalaria Juncea: Growth, Glomalin Content and Acid Phosphatase Activity in a Copper-Contaminated Soil. *Rev. Bras. Cienc. Solo* **2018**, *42*, e0170245. [CrossRef]
44. Marcelo, A.V.; Corá, J.E.; Fernandes, C.; dos Martins, M.R.; Jorge, R.F. Crop Sequences in No-Tillage System: Effects on Soil Fertility and Soybean, Maize and Rice Yield. *Rev. Bras. Cienc. Solo* **2009**, *33*, 417–428. [CrossRef]
45. Collier, L.S.; Castro, D.V.; Dias Neto, J.J.; Brito, D.R.; Ribeiro, P.A.; de Manejo, A. Da Adubação Nitrogenada Para o Milho Sob Palhada de Leguminosas Em Plantio Direto Em Gurupi, TO. *Ciência Rural.* **2006**, *36*, 1100–1105. [CrossRef]
46. Pavinato, P.S.; Cherubin, M.R.; Soltangheisi, A.; Rocha, G.C.; Chadwick, D.R.; Jones, D.L. Revealing Soil Legacy Phosphorus to Promote Sustainable Agriculture in Brazil. *Sci. Rep.* **2020**, *10*, 15615. [CrossRef]
47. Hansen, V.; Müller-Stöver, D.; Gómez-Muñoz, B.; Oberson, A.; Magid, J. Differences in Cover Crop Contributions to Phosphorus Uptake by Ryegrass in Two Soils with Low and Moderate P Status. *Geoderma* **2022**, *426*, 116075. [CrossRef]
48. Blanco-Canqui, H.; Drewnoski, M.E.; Rice, D.G. Does Harvesting Cover Crops Eliminate the Benefits of Cover Crops? Insights after Three Years. *Soil Sci. Soc. Am. J.* **2021**, *85*, 146–157. [CrossRef]