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Nutrient Accumulation in Cover Crops under Contrasting Water Regimes in the Brazilian Cerrado

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Abstract: Brazilian Cerrado has a dry period, and the inclusion of new species for diversification in the production system needs to be drought-tolerant. This work aimed to evaluate biomass and nutrient accumulation in species with potential as cover crops and grain crops under different water levels. Irrigation treatments were obtained through an irrigation bar with sprinklers with increasing water flows to create a continuous gradient. The experimental design randomized complete blocks in split plots with four replications. The main plots were composed of four water regimes (167 mm, 268 mm, 381 mm and 432 mm), and the subplots were formed by the following cover crops: *Amaranthus cruenthus*, *Chenopodium quinoa* and *Pennisetum glaucum*, the latter already used for this purpose. *Amaranthus cruenthus* and *P. glaucum* recorded the highest dry biomass (10.16 and 9.75 Mg ha^{-1}, respectively). Dry biomass production and the cellulose contents decreased with the reduction of water availability for all species. *A. cruenthus* was the species that most accumulated P (37.42 kg ha^{-1}), K (416.92 kg ha^{-1}), Mg (30.88 kg ha^{-1}), S (43.53 kg ha^{-1}), Fe (2.22 kg ha^{-1}), B (0.124 kg ha^{-1}) and Zn (0.240 kg ha^{-1}). *Amaranthus cruenthus* produced the highest yield. Under high and low water availability conditions, *A. cruenthus* presents potential as a cover crop and grain cash crop, in addition to accumulating more nutrients; *P. glaucum* has potential as a cover crop and *C. quinoa* only for grain production.

Keywords: soil protection; water stress; *Amaranthus cruenthus*; *Chenopodium quinoa*; *Pennisetum glaucum*

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1. Introduction

The Cerrado is one of the largest and most important biomes in Brazil, with an area of 2,036,448 km^2, and represents about 24% of the national territory [1]. Agriculture in the Cerrado region is characterized by two cultivation periods: the main crop season (period with the highest rainfall) from October to January and a second crop "off-season" from February to May. As a result, water shortages are expected to impact up to two-thirds of humanity between 2010 and 2050, and subsistence farmers worldwide would benefit from nutrition and drought-tolerant cover crops [2].

Winter cultivation in Cerrado, between May and September, presents low rainfall, and irrigation is used. Currently, one of the major challenges in the Cerrado region is to obtain species with a high potential for grain production in the second crop and simultaneously produce enough biomass for coverage and protect the soil during the off-season, since water availability for the plants in these periods is reduced [3]. The use of cover crop in an agricultural system is mainly beneficial for soil and water conservation [4]. Cover crops such as *Vicia villosa* improved the soil moisture preceding the soybean growing season in very fine sandy loam soil [5]. On the other hand, Hunter et al. [6] observed that cover crops, such as clover and radish, neither ameliorated nor exacerbated drought stress tolerance in the following cash crop: maize; in the same work, the authors obtained a negative effect of rye on the subsequent crop. Cover crops, in addition to soil protection against degradation agents such as erosion and compaction, can restore considerable amounts of nutrients since they absorb nutrients from the soil subsurface layers and release them on the soil surface by decomposition of plant residues [7–9].

The use of species tolerant to water stress with slower decomposition rate favors soil coverage and a gradual release of nutrients for subsequent crops. Crop residue accumulation and nutrient release into soil depend on their quantity and quality, which influences the processes of plant decomposition [7,10]. Cellulose, hemicelluloses, lignin contents and C/N ratio are important indicators of crop residue quality for maintaining soil covered due to slower decomposition [11]. Moreover, the decomposition rates of plant residues are negatively related to the number of compounds rich in aromatic rings and that is difficult to break down, such as lignin [12].

Pennisetum glaucum (L.) R. Brown is a traditional crop in West Africa and Asia, with exceptional adaptation to abiotic stresses [13]. It is one of the most cultivated cover crop species in the Cerrado region due to its greater tolerance to drought, high biomass production and efficient nutrient cycling [8,14,15], and it is adapted to semi-arid regions [16].

Some species characterized as pseudocereals are potential alternatives as cover crops because of their adaptation to the Cerrado region [14]. Among them, *Amaranthus cruenthus* is a widely cultivated species that produces grains; its leaves are also used for human and animal consumption [17]. In addition, *A. cruenthus* has pivoting roots with abundant lateral roots, which favor the absorption of water and nutrients [18], and is adapted to arid regions or places with prolonged drought periods.

Chenopodium quinoa (Willd) is a pseudocereal species from the Andes region and is considered an exceptional crop for its potential to contribute to food security [19]. The species is well-adapted to abiotic stresses, such as water stress, low temperatures, salinity and nutrient-poor soils [20,21]. In addition, this species has well-adapted to the Cerrado region due to the amount of biomass and grain production and is an alternative for soil protection in the no-tillage system [22].

Cover crops may have a secondary purpose, grain production, which would promote economic sustainability, providing income from the commercialization of the grains. The pseudocereals are species with high potential for grain production, and studies have reported *A. cruenthus* productivity ranging from 990 to 3692 kg ha^{-1} [23,24]. Some *C. quinoa* genotypes produce up to 8.34 t ha^{-1} with a water regime of 389 mm during the crop cycle [25]. Additionally, the grains of these two species present high nutritional value; are rich in macronutrients and micronutrients, including vitamins and minerals, high protein and essential amino acids; and are considered functional foods [19,26].

Therefore, we have tested the hypothesis that, in addition to *Pennisetum glaucum*, *A. cruenthus* and *C. quinoa* consist of alternative species, as they have potential as cover crops, nutrient accumulation and grain yield, even in conditions of low water availability. The objective of this work was to evaluate biomass production and nutrient accumulation in species with potential as cover crops and grain production under different water levels.

2. Materials and Methods

The experiment was conducted at the Embrapa Cerrados in Planaltina, DF, Brazil, located at the geographic coordinates: 15°35′30″ S and 47°42′30″ W. The climate of the region is characterized as Aw, according to the Köppen classification, with two well-defined seasons (dry and rainy). Summer is warm and humid, with dry spells during the rainy season, called *veranicos*. It presents average annual rainfall of 1400 mm and an average temperature of 21.3 °C [27]. The monthly average temperature and rainfall data during the experiment are presented in Figure 1.

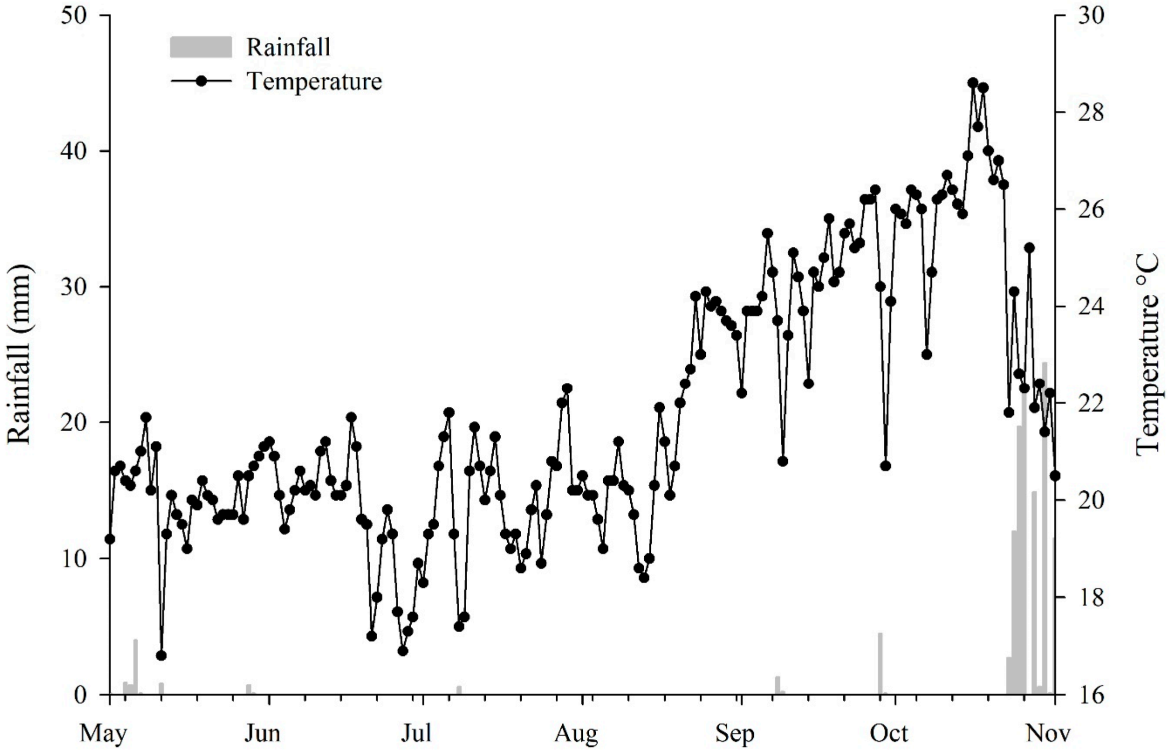

Figure 1. Average precipitation and temperature of the experimental area from May to November 2015. Data were obtained from an automatic station located next to the experimental area.

The soil of the experimental area is classified as clayey Oxisol (Typic Haplustox) [28] and presents the following chemical composition 0–20 cm layer: pH (H_2O) = 5.77 and Ca ($cmol_c$ dm^{-3}) = 3.34, Mg ($cmol_c$ dm^{-3}) =1.41, K (mg dm^{-3}) = 207.55, H + Al ($cmol_c$ dm^{-3}) = 4.52, P (mg dm^{-3}) = 48.56, S (mg kg^{-1}) = 19.71 and organic matter (g kg^{-1}) = 26.0.

The history of the experimental area over the last nine years is presented in Table 1. Before being cultivated with soybeans in the 2005/2006 crop season, the area was under native Cerrado vegetation.

Table 1. Description of the cultivation history of the studied area between 2005 and 2015.

Crop Season	**Period**	
	Winter	**Summer**
2005/2006	Fallow	Soybean
2006/2007	Fallow	Soybean
2007/2008	Fallow	Soybean
2008/2009	Fallow	Soybean
2009/2010	Fallow	Soybean
2010/2011	Fallow	Soybean
2011/2012	Soybean under different water regimes	Fallow
2012/2013	Wheat under different water regimes	Soybean
2013/2014	*A. cruenthus*, *P. glaucum* e *C. C. quinoa* under different water regimes	*Crotalaria juncea*
2014/2015	*A. cruenthus*, *P. glaucum* e *C. C. quinoa* under different water regimes	*Zea mays*

The experimental design was randomized blocks with split plots and four replications. The main plots were composed of four water regimes (167 mm, 268 mm, 381 mm and 432 mm), and the subplots were formed by the following cover crops: *Amaranthus cruenthus; Chenopodium quinoa* "Genotype derived from BRS Piabiru" and *Pennisetum glaucum*. The plots measured 24 m × 3.2 m, and the subplots measured 8 m × 3.2 m. Each plot was composed of 8 lines, spaced at 0.40 m.

Cover crops were sown in the first week of May 2015. Seeds were sown manually under a no-tillage system. The seeding density was 200 seeds m^{-1} for *A. cruenthus*, 150 seeds m^{-1} for *C. quinoa* and 58 seeds m^{-1} for *P. glaucum*. The high seeding rate was applied to compensate germination failures due to the small seed size. Twenty days after emergence (DAE), thinning was performed, obtaining 10 plants m^{-1} for *A. cruenthus* and 20 plants m^{-1} for *C. quinoa* and *P. glaucum.*

NPK fertilization at planting was used with the formulation 04-30-16 at 400 kg ha^{-1}. Thirty days after seedling emergence, nitrogen topdressing was applied at a dose of 100 kg N ha^{-1} as urea. To avoid the competition of invasive plants, manual weeding was performed.

The water regimes were obtained using a sprinkler irrigator bar 40 m wide, connected to a spool with adjustable speed and ten sprinklers were installed on each side of the bar. During the 35 of germination, irrigation was uniform, and ten irrigations were performed, totaling 135 mm. After this period, the line source methodology was adapted [29], using sprinklers with decreasing sizes from the central area to the end of the experimental area. The sprinklers overlapped and promoted a decreasing gradient of water. For each side of the irrigation bar, 4 plots were delimited, with a linear distance between them, representing the water regimes (WR). In this phase, 13 irrigations were performed. The accumulated depths of the uniform plus variable irrigations were 167, 268, 381 and 432 mm for the four WRs. Two rows of collectors parallel to the irrigation line were installed to measure the volume of water applied to each irrigation. Irrigations were carried out according to the irrigation monitoring program in the Cerrado [30], using wheat crop as a reference, the agrometeorological indicators of the region, the soil type and the date of germination.

2.1. Production of Dry Biomass and Structural Components (Lignin, Cellulose, Hemicellulose and Lignin/N)

For dry biomass production, a sample was collected from each plot during the flowering of cover crops, with an area of 3 m^2, in the four central lines, with 2.5 m in length. The collected material was kept at 65 °C for 72 h until reaching a constant weight.

From dry biomass samples, three subsamples were collected to determine lignin, cellulose and hemicellulose contents by the sequential method [31], through of the analysis of fiber neutral detergent (FND) and fiber acid detergent (FAD), modified by Komarek [32], using an Ankom fiber apparatus (Ankom Technology Corp., Fairport, NY, USA). Lignin analysis was determined by digestion of FAD residue with 72% sulfuric acid, with the extracts of cellulose and hemicellulose, producing lignin inorganic matter as a residue. Hemicellulose and cellulose were quantified by the difference between the FND and FAD residues and between the FAD and lignin residues, respectively. The difference between the acid digestion residue and after burning at 600 °C for four hours was determined the lignin content.

Accumulation of Macro and Micronutrients in the Shoot

The concentrations of phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), sulfur (S), copper (Cu), manganese (Mn), zinc (Zn), boron (B) and iron (Fe) in the dry biomass were determined using an inductively coupled plasma optical emission spectrophotometer (ICP-OES, Thermo Cientific, 7000, Waltham, MA USA). The nitrogen (N) concentration in the plants was determined by the Kjeldahl method. The accumulation of macro and micronutrients in plants was calculated by the product between the concentration of each element in the plant tissue and the amount of dry biomass produced. The results were expressed in kg ha^{-1}.

2.2. Grain Productivity

Grain yield was obtained by mechanical harvesting of plants in an area of 7.2 m^2 $plot^{-1}$. A subsample was oven dried at 65 °C until constant weight to determine the moisture of the grains. Productivity was corrected to 13% humidity, and the results were expressed in kg ha^{-1}.

2.3. Statistical Analysis

Data were subjected to analysis of variance (ANOVA) and the comparison of means was performed by the Tukey's test was used, at 5% of probability, using statistical software SAS [33]. The statistical model was adjusted using the SAS PROC MIXED through the restricted maximum likelihood method (reml). The variation sources were water regimes (plots), cover crops (subplots) and their interactions. For the variables in percentages (cellulose, hemicellulose and lignin), data were transformed into square root of arcsine (x/100). These transformations were necessary to obtain data residue normality.

Data were also submitted to the redundancy analysis (RDA) in the CANOCO® statistical program [34] after being transformed into Log C + 1 and meeting the criterion of the gradient length lower than 3 of the distended correspondence analysis (DCA) [35]. The variables (P, K, S, Al, Fe, Cu, Ca, Mn, Mg, B and Zn) were analyzed as explanatory variables, and the contents of lignin, cellulose, hemicellulose and dry biomass were analyzed as response variables. The Monte Carlo permutation test (permutations = 999) was carried out to determine which explanatory variables were most significant ($p \leq 0.05$) in the model.

3. Results

3.1. Production of Dry Biomass and Structural Components (Lignin, Cellulose, Hemicellulose and Lignin/N)

Amaranthus cruenthus and *P. glaucum* presented the highest dry biomass (BS) production, with 10.16 and 9.75 Mg ha^{-1} ($p < 0.05$), respectively (Table 2), and *C. quinoa* was the species with the lowest BS (7.31 Mg ha^{-1}), 28% smaller than the best species (A. *cruenthus). Penisetum glaucum* was the species with the lowest concentration of lignin (28% lower than *C. quinoa*) and higher concentration of cellulose and hemicellulose: 12 and 45% higher cellulose and hemicellulose content, respectively, compared with *C. quinoa*. The cellulose, hemicellulose and lignin concentrations in *A. cruenthus* and *C. quinoa* were statistically similar.

Table 2. Dry biomass (BS) and contents of cellulose, hemicellulose, lignin and lignin/N ratio in the cover crops (*A. cruenthus, P. glaucum* and *C. quinoa*) and in the water regimes (167, 268, 381 and 432 mm).

Treatment	**Dry Biomass (Mg ha^{-1})**	**Cellulose (%)**	**Hemicellulose (%)**	**Lignin (%)**	**Lignin/N**
		Cover crop			
C. quinoa	7.31 b	26.75 b	13.22 b	4.28 a	0.22 a
P. glaucum	9.75 a	30.41 a	24.39 a	3.64 b	0.22 a
A. cruenthus	10.16 a	27.36 b	13.56 b	4.35 a	0.24 a
		Water regime (mm)			
167	6.84 b	26.20 b	18.19 a	3.68 a	0.20 a
268	9.47 a	28.43 a	17.03 ab	4.40 a	0.26 a
381	9.94 a	29.43 a	17.28 ab	4.44 a	0.24 a
432	10.04 a	28.63 a	15.74 b	3.85 a	0.21 a

Means followed by the same letter in each column do not differ statistically by Tukey's test at 5% probability.

Regarding the water regime (WR), the lowest BS production occurred in the lower water regime (167 mm), which differed from the other regimes ($p < 0.05$). Comparing the highest water regime (432 mm) with the lowest one (167 mm), there was a 31% reduction in BS production. Increased water availability enhanced the cellulose and reduced the hemicellulose contents. The lignin contents were not influenced by WRs. No significant difference was obtained for the lignin/N ratio for cover crops and water regimes.

3.2. Accumulation of Macro and Micronutrients in the Shoot

A significant effect of cover crops and water regimes was obtained in the accumulation of macro and micronutrients. The interaction between water regimes and cover crops was significant ($p < 0.05$) only for P, Ca, B and Zn (Table 3). In general, *A. cruenthus* was the species that accumulated more nutrients. Under higher water availability (432 mm), this species accumulated up to 37.42 kg ha^{-1} of P; *P. glaucum* reached up to 30.88 kg ha^{-1} (381 mm), and *C. quinoa* reached 24.29 kg ha^{-1}, 33% lower than *A. cruenthus,* with the same water amount of applied water (432 mm).

Table 3. Interaction between the water regime and cover crops in the accumulation of phosphorus (P), calcium (Ca), boron (B) and zinc (Zn) in the shoot biomass of the three cover crop species.

Water Regime (mm)	**Cover Crop**		
	A. cruenthus	***P. glaucum***	***C. quinoa***
	P (kg ha^{-1})		
167	14.40 Ac	10.32 Bc	7.11 Cc
268	31.04 Ab	20.60 Ab	15.36 Bb
381	38.81 Aa	30.88 Ba	21.46 Cab
432	37.42 Aab	26.39 Bab	24.29 Ba
	Ca (kg ha^{-1})		
167	79.24 Ac	23.94 Ba	28.47 Bb
268	141.09 Ab	36.05 Ba	51.18 Bab
381	141.03 Ab	40.65 Ba	60.81 Ba
432	162.36 Aa	33.48 Ca	75.99 Ba
	B (kg ha^{-1})		
167	0.042 Ac	0.016 Ba	0.028 Ab
268	0.088 Ab	0.020 Ca	0.042 Bb
381	0.110 Aa	0.026 Ca	0.065 Ba
432	0.124 Aa	0.021 Ca	0.069 Ba
	Zn (kg ha^{-1})		
167	0.064 Ac	0.067 Ab	0.070 Ab
268	0.150 Ab	0.102 Aab	0.128 Aa
381	0.179 Ab	0.125 Aa	0.157 Aa
432	0.240 Aa	0.121 Ca	0.162 Ba

Means followed by the same small letter in each column, and capital letter in a row, do not differ statistically by Tukey´s test at 5% probability.

The reduction of water availability resulted in a lower accumulation of P in the shoot for all species. *C. quinoa* was the most sensitive to a lower water regime, with a reduction of 70% in the P content. For *A. cruenthus* and *P. glaucum*, these reductions were 62% and 66%, respectively.

A. cruenthus was the species with the highest Ca content in all WRs ($p < 0.05$), with values up to 162.36 kg ha^{-1}. *P. glaucum* and *C. quinoa* accumulated similar amounts of Ca, except for WR 432 mm, which presented greater accumulation in *C. quinoa.* The increase in water availability positively influenced the accumulation of this nutrient in *A. cruenthus* and *C. quinoa*. As with the P content, the Ca accumulation was more sensitive to lower water availability in *C. quinoa*, with a reduction of 62% for this species and 51% and 41% for *A. cruenthus* and *P. glaucum*, respectively.

The B content was increased by 66.33% and 59.42% for *A. cruenthus* and *C. quinoa*, respectively, when comparing the highest and lowest water regime. *P. glaucum* accumulated the same amount of B, regardless of the applied water. Among the species, in general, a greater accumulation of B was observed in *A. cruenthus*.

The three species showed similar contents of Zn in the 167, 268 and 381 mm water regimes (Table 3). In WR 432 mm, *A. cruenthus* and *P. glaucum* presented the highest and lowest accumulation of Zn ($p < 0.05$), respectively. Unlike that observed for P and Ca, *A. cruenthus* showed the lowest Zn concentrations at the lowest water regime. The reduction of Zn content was equivalent to 72% for this species, 57% for *C. quinoa* and 47% for *P. glaucum*, when comparing the highest and the lowest water regime. *P. glaucum* was the species less affected by the reduction of water availability in Ca and Zn contents.

N content was similar among the species (Table 4). *A. cruenthus* accumulated most K (416.92 kg ha^{-1}), Mg (30.88 kg ha^{-1}), S (43.53 kg ha^{-1}) and Fe (2.22 kg ha^{-1}). For Cu, this species presented similar values to *P. glaucum* and *C.quinoa;* for Mn, this species presented similar content to *C. quinoa*. *P. glaucum* had the lowest levels of K and Mg ($p < 0.05$) and showed similar contents of S, Fe and Mn compared to *C. quinoa*. Although it presented lower values than *A. cruenthus*, it is worth mentioning the high capacity of *C. quinoa* to accumulate K (367.89 kg ha^{-1}). There was a significant reduction in the concentration of these nutrients in the plant biomass with the decrease in water availability ($p < 0.05$), except for Fe, which was not influenced by the water regimes.

Table 4. Isolated effect of cover crops and water regimes on the accumulation of macro- and micronutrients in the shoot biomass of the three cover crops.

Treatment	N	K	Mg	S	Fe	Cu	Mn
Cover crop kg ha^{-1}							
A. cruenthus	182.68 a	416.92 a	30.88 a	43.53 a	2.22 a	0.03 ab	0.17 a
P. glaucum	165.51 a	200.37 c	12.87 c	21.02 b	1.46 b	0.04 a	0.10 b
C. quinoa	144.88 a	367.89 b	18.63 b	23.22 b	1.65 b	0.02 b	0.13 ab
Water regime (mm)							
167	141.91 b	222.84 b	13.69 b	18.03 c	1.82 a	0.02 c	0.11 b
268	168.19 a	345.30 a	21.49 a	27.69 b	1.85 a	0.03 b	0.14 ab
381	166.52 a	380.11 a	23.42 a	34.28 a	1.67 a	0.03 b	0.13 ab
432	180.80 a	365.32 a	24.56 a	37.02 a	1.78 a	0.04 a	0.16 a

Means followed by the same letter in each column do not differ statistically by Tukey´s test at 5% probability.

3.3. Grain Productivity and Redundancy Analysis (RDA)

The highest grain yields *of A. cruenthus* and *C. quinoa* were between 3549.45 kg ha^{-1} and 3488.86 kg ha^{-1}, respectively, in WR 432/381 ($p < 0.05$) (Table 5). *A. cruenthus* produced higher grain production than *C. quinoa* under the two intermediate regimes and did not differ under the extreme ones (168 and 432 mm). However, *A. cruenthus* presented a reduction of 71% when comparing the regime with the highest productivity (381 mm) with the lowest (167 mm). For *C. quinoa*, the reduction was 80%. *P. glaucum* did not produce grains.

Table 5. Interaction between water regimes and cover crops in grain yield under four water regimes.

Water Regime (mm)	Cover Crop	
	C. quinoa	***A. cruenthus***
	kg ha^{-1}	
167	691.58 Ac	1018.43 Ac
268	1904.31 Bb	2875.02 Ab
381	2882.90 Ba	3866.89 Aa
432	3488.86 Aa	3549.45 Aa

Means followed by the same small letter in each column, and capital letter in a row, do not differ statistically by Tukey´s test at 5% probability.

In the redundancy analysis, two groups were formed for *A. cruenthus* species (Figure 2A). These groups presented different relations with the dynamics of the explanatory variables. The group was most closely related to the explanatory variables were WR 381 and 432 mm

(Figure 2B). In contrast, the 167 and 268 mm water regimes for *A. cruenthus* species presented the lowest relation with the explanatory variables. However, there was a partial overlap in *C. quinoa* and *P. glaucum*, especially in the intermediary water regimes (268 and 381 mm) (Figure 2C). Among the explanatory variables of the model, P, Cu, Mn, S and Mg were the significant variables, according to the Monte Carlo permutation test (Table 6).

Table 6. Summary of conditional effects between plant nutrients based on Monte Carlo permutation test.

Chemical Attribute	Lambda (λ)	Contribution (%)	F-Test	*p*-Value	
P	0.22	37	12.63	0.0020	***
Cu	0.08	13	4.41	0.0080	***
Mn	0.07	12	5.68	0.0040	***
S	0.04	7	3.49	0.0320	**
Mg	0.04	7	3.67	0.0320	**
Al	0.04	7	2.81	0.0760	ns
Zn	0.02	5	1.57	0.2060	ns
K	0.02	3	1.56	0.2120	ns
Fe	0.02	3	1.60	0.2160	ns
Ca	0.02	3	1.43	0.2360	ns
B	0.01	3	1.26	0.3040	ns

Levels of significance: *** ($p \leq 0.01$), ** ($p \leq 0.05$) and ^{ns} (non-significant).

In the separation of WRs, the most contrasting water regime, which was not related to the dynamics of the explanatory variables, was 167 mm (Figure 2B). WR 381 mm was the most closely related to the dynamics of the explanatory and response variables (Figure 2C). The length of the response vectors in the ordering diagram (Figure 2A–C) reflected their contribution to the model. The relationship between the variables is expressed in the diagram by the angle formed between them. Thus, dry biomass showed greater contribution among the variables, followed by the lignin and cellulose contents. A possible no correlation between dry biomass and the lignin content was observed, expressed in the diagram as an approximate angle of 90° between these vectors. The lignin content was correlated with *C. quinoa* species in the 381-mm water regime (Figure 2C), whereas the BS was less correlated with all water regimes for this species (Figure 2C).

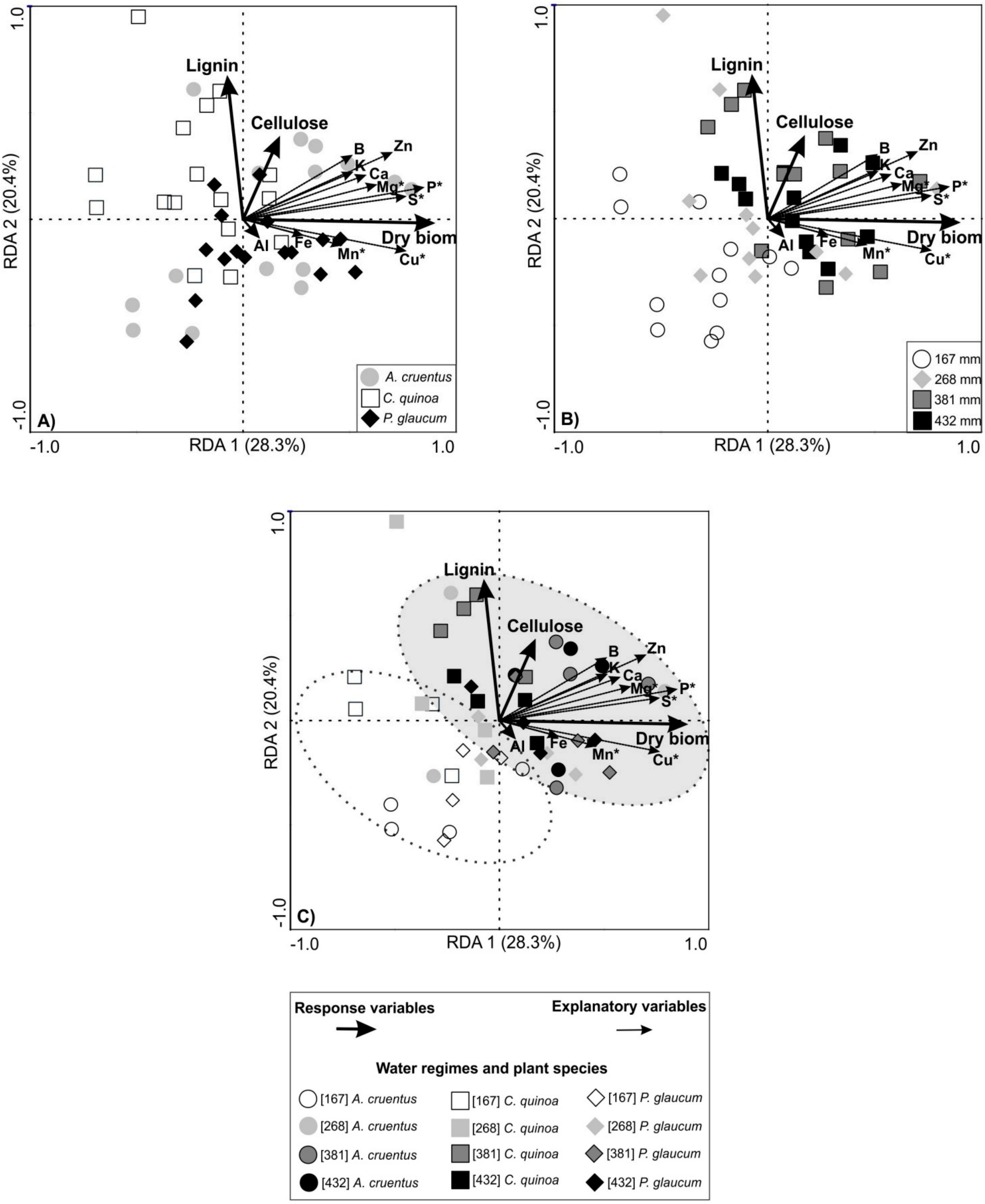

Figure 2. Order diagram of the redundancy analysis (RDA) with the explanatory variables (P, K, S, Al, Fe, Cu, Ca, Mn, Mg, B and Zn) and the variable responses (lignin, cellulose and dry biomass contents) based on the Monte Carlo permutation test (permutation = 999) distributed according to plant species (**A**; n = 16), water regime (**B**; n = 12) and both (**C**; n = 4). Asterisk denotes significance ($p < 0.05$), according to Table 6.

4. Discussion

4.1. Dry Biomass Production and Structural Components (Lignin, Cellulose and Hemicelluloses)

In the Cerrado region, the residual crop and cover crops on the soil surface are between 2.38 to 10.64 ton ha^{-1} [36]. Biomass production for the legumes ranged from 1420 (velvet bean) to 4807 kg ha^{-1} (sesbania) in North Carolina in a clayed soil with an adequate level of P and K [37]. In the present work, *A. cruenthus* (10.16 Mg ha^{-1}) and *P. glaucum* (9.75 Mg ha^{-1}) presented BS production close to the highest amount of crop residues on the soil surface. *Penisetum glaucum* is commonly used cover crop in the Cerrado region due to its rapid growth and establishment and high BS production. In addition, this plant is tolerant to water stress, which makes it promising for use in the Cerrado [14], especially due to climate change, with precipitation instability and extreme temperatures [14]. Therefore, *A. cruenthus* is useful as a cover crop in the Cerrado region in dry and rainy years.

A. cruenthus is a crop recently introduced in the Cerrado region. The BS values obtained in the present study were much higher than those obtained by other authors [24]. This difference in productivity may be related to climatic conditions, water availability provided by the different regimes, genotype used and fertilization. Fertilization is carried out to produce grains, constituting an unusual practice in the cultivation of cover crops, which use only residual fertilization of the main crop. This practice must be changed considering the benefits of cover crops. Due to the high production of dry biomass obtained in this work, sufficient for soil protection, this species can be considered an alternative as a cover crop in the Cerrado, resulting in greater diversification of the production system.

The maintenance of plant biomass on the soil surface depends mainly on the biomass decomposition rate, which is controlled by its quality, which is directly related to its organic components (cellulose, hemicelluloses and lignin). Alternatively, they must improve soil fertility by cycling and releasing nutrients, gradually supplying the needs of succession crops [9].

Cellulose is more labile and generally decomposes faster than lignin due to its composition and chemical structure, consisting of C less recalcitrant, such as alkyls and O-alkyls [38,39]. Thus, higher decomposition rates are observed in plants with higher cellulose content and lower lignin content [15]. In the present work, *A. cruenthus* and *P. glaucum* presented higher biomass production, whereas *P. glaucum* showed higher cellulose content (30.41%) and lower lignin (3.64%). Pacheco et al. [15] evaluated biomass production and nutrient cycling by cover crops in the Cerrado and found higher decomposition rates in *P. glaucum* and *U. ruziziensis*. The authors attributed the results to the lower concentrations of lignin of these species and concluded that it altered the rate of decomposition of the cover crops. Thus, *P. glaucum* presents a greater potential for nutrient release in the soil, as it may present faster decomposition than *A. cruenthus*. However, *A. cruenthus* presents greater potential to protect the soil due to its higher lignin contents than *P. glaucum*. Besides, *A. cruenthus* can be used as soil protection, especially in degraded soils, as it has slow decomposition compared with *P. glaucum.* In addition, the nutrient release could be used not only in the next crop but also in the long-term or with subsequent perennial crops.

4.2. Accumulation of Macro and Micronutrients in the Shoot

The accumulation of nutrients by plants is influenced by the species/cultivar, type of soil, environmental conditions, nutrient characteristics, and water availability, which mainly affect ion-root contact processes [40]. N, Ca, Mg, S, B, Cu, Fe, and Zn are absorbed by roots through mass flow; diffusion is the process for absorption of P and K, and root trapping for Mn. Diffusion also contributes to Ca absorption, while water stress reduces plant growth and the diffusion and mobility of nutrients in soil [41].

The accumulation of macro and micronutrients was related to the increase in water availability. This may be associated with the movement of these nutrients in the soil by mass flow and diffusion. Water stress reduces the mobility of P and its transfer from soil to root and subsequent transport to the stem, as this nutrient moves predominantly by diffusion through the difference in soil concentration [42,43]. Drought tolerance and plant water use efficiency can be enhanced by adequate phosphorus nutrition [44].

Dry biomass production of the three species in the most stressed water regime (168 mm) showed that *C. quinoa* was the species with lower phosphorus accumulation. This fact may have contributed to the lower drought tolerance and lower biomass production of this species, considering that P is the main limiting nutrient in the Cerrado region. Among the mechanisms proposed to justify the effect of phosphorus on root growth are the increase in root growth, stomatal conductance, leaf area and photosynthesis, and increased cell membrane stability [45,46].

Potassium is another nutrient that, despite being more mobile than P in the soil, under water stress conditions, has reduced absorption and translocation by the roots [47]. Water stress dramatically affects the opening and closing of the stomata and, consequently, the photosynthetic activity [25,46]. The osmotic adjustment or regulation, cell elongation, root growth promotion, stomatal regulation as well as reactive oxygen detoxification are pathways of potassium activation towards greater tolerance to drought by plants [47].

Nutrient uptake is also directly related to the development of the roots, as their growth is influenced by water availability in the soil. Therefore, plants with greater specific root length and a high proportion of fine roots [48] absorb nutrients more efficiently.

Amaranthus cruenthus was the species that most accumulated P (37.42 kg ha^{-1}), K (416.92 kg ha^{-1}), Mg (30.88 kg ha^{-1}), S (43.53 kg ha^{-1}) and Fe (2.22 kg ha^{-1}) in the shoot. Cover crops with great nutrient accumulation can release nutrients to the main crop in rotation, succession, or consortium [49,50]. *P. glaucum* showed the lowest concentration of nutrients; however, it presented higher accumulation of K and Ca than those obtained by Pacheco et al. [15], who found 155 kg ha^{-1} of K and 28 kg ha^{-1} of Ca for this species. *A. cruenthus* and *C. quinoa* presented high levels of P and K. These nutrients play an important role in the preservation and transfer of energy in metabolism, osmotic and stomatal regulation in plants, which are fundamental of water stress tolerance [47].

4.3. Grain Productivity and Redundancy Analysis (RDA)

No grain yield was observed in *P. glaucum*, probably due to 76 days with temperatures below 15 °C (Figure 1) during the crop cycle. Low temperatures (13 to 16 °C) may favor the appearance of sterile plants in this species. Jayme-Oliveira et al. [14] evaluated the performance of cover crops in the Cerrado between May and October and obtained 115 h of temperatures below 16 °C, which may have prevented the production of grains in *P. glaucum*.

A. cruenthus (3866.89 kg ha^{-1}) and *C. quinoa* (3488.86 kg ha^{-1}) showed high productivity. Da Silva et al. [25] studied several *C. quinoa* genotypes and obtained high yields in the Brazilian Cerrado under four water regimes and found yields between 8570 and 2580 kg ha^{-1}, comparing the highest (480 mm) and the lowest water regimes (150 mm). For *A. cruenthus*, yields ranging from 990 to 3692 kg ha^{-1} are reported [24]. In the present study, *A. cruenthus* showed higher productivity than those obtained by [51], but for *C. quinoa* under irrigation, productivity was higher, mainly in WR 432 mm. However, when cultivated under severe stress (268 and 167 mm), significant reductions in productivity were observed for both *A. cruenthus* (71%) and *C. quinoa* (80%). In severe water deficit, intense morphological and physiological changes are observed in plants [25,52], directly affecting grain yield. Jayme-Oliveira et al. [14] evaluated the growth and development of *A. cruenthus* and *C. quinoa* under different water regimes and observed reductions in leaf area, leaf number and height of *A. cruenthus* and *C. quinoa* under water stress.

According to the RDA, P was one of the significant variables in the model, followed by Cu, S, Mn and Mg. The P was correlated with the *A. cruenthus* species in the WR 381 mm. Likewise, this result was observed in the univariate analysis, in which *A. cruenthus* was the species with the highest accumulation of P in the dry biomass (38.81 kg ha^{-1}).

5. Conclusions

Amaranthus cruenthus produced higher nutrient accumulation than *P. glaucum* and C. *quinoa,* and higher biomass than *C. quinoa.* In addition, in general, this species produced a higher yield than *C. quinoa*, especially in lower water regimes. *A. cruenthus* can be recommended as a dual purpose crop for the target region. Future research should test it in the productive system in Cerrado farm conditions with several options as subsequent annual or perennial crops. *C. quinoa* can be indicated for grain production but not as cover crop.

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