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Can Soil Moisture and Crop Production Be Influenced by Different Cropping Systems?

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Abstract: The different conditions of soil vegetation cover combined with irrigation management and/or agricultural production systems can influence soil moisture content and crop yields. This study investigated the impact of agricultural production systems and center pivot irrigation management on soil moisture content during the cultivation of soybean and off-season corn crops. Two field experiments were conducted during the 2018–2019 growing season in tropical Cerrado soil conditions; one experiment consisted of the application of three irrigation water depths (0%, 50%, and 100% of the crop evapotranspiration) during soybean cultivation in a no-tillage system under ruzigrass (*Urochloa ruziziensis*) straw, and the second experiment consisted of the intercropped or nonintercropped cultivation of corn hybrids with ruzigrass in an agricultural area with and without the influence of eucalyptus reforestation. The volumetric soil moisture was measured using an electronic soil moisture meter (Hidrofarm), and the 1000-grain mass and yield of the soybean and corn were measured in the two trials. Irrigation and the no-till system did not influence soybean yields. The soybean cultivars NA 5909 RG and TMG 7067 IPRO presented TGM above 180 g, and this represented on average a 22% higher TGM than the BMX DESAFIO RR and CD 2737 RR. The presence of eucalyptus forest promoted a 1.5% increase in soil moisture in the corn crop. Soil management systems, such as irrigation, use cover crops, which may not increase the productivity of soybean and corn crops as expected.

Keywords: forest; intercropped; irrigation management; moisture soil sensor; cultivars

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1. Introduction

In recent decades, agricultural production in the Cerrado region has been an important driver of the Brazilian economy and agribusiness. For the next 10 years, grain production projections indicate that Brazilian grain production should reach 320 million tons, which corresponds to an increase of 25.5% over the current 2021/2022 harvest, which was 255 million tons [1,2]. However, this increase in grain production is inherent to the adoption of technologies and management practices developed for Brazilian agricultural systems.

Agricultural areas in the Cerrado region are ideal for developing Brazilian agricultural production, primarily due to the favorable tropical climate and soils with good physical

characteristics that facilitate mechanization operations and management practices [1]. However, crop yields in the Cerrado have often been negatively impacted by rainfall deficits and severe drought during cultivation [3,4]. Currently, drought or prolonged rainfall deficits are a major natural issue that endangers food and water safety in large regions of the world's agriculture [3].

Irrigation is a technology that can mitigate the negative impacts of drought during the rainy season on crop yield [5]. In addition, irrigation can also intensify agricultural land use by enabling grain production during the dry season in the Cerrado region, which increases agricultural yield [5]. However, the use of irrigation requires a high level of capital investment from farmers and specialized technical assistance to provide rational water use and sustainable grain production [6].

Soil water balance helps determine crop irrigation needs and improves irrigation system management [7]. Therefore, sustainable irrigation management requires knowledge of soil water availability during plant development stages and soil water storage capacity [5]. A practical and easy alternative to measuring soil water availability for crops is using tensiometers or soil moisture sensors [8]. Soil moisture sensors deployed in the field have high accuracy in demonstrating soil moisture over environmental variations and dry and humid seasons [9]. The use of soil moisture sensors can reduce the loss of water from the soil and is efficient for irrigation programming [10]. Chakraborty et al. [11] observed that cover crops improved the soil water storage for cash crops compared to no cover crops using soil moisture sensors.

In addition to irrigation, adopting agricultural conservation systems such as the agroforestry system (AFS) can also improve the production environment and grain yield of the main agricultural crops in the Cerrado region [12]. The AFS has been widely used in Brazil and is characterized by land use management in which trees are grown in combination with crops [12,13]. This production system is considered an excellent alternative for developing sustainable and competitive agriculture, especially for improving the physical, chemical, and biological properties of the soil and reducing the impact of intensive land use [13,14]. However, the water requirement of trees is greater than that of crops, but this depends on the amount of established tree population [15]. In this sense, soil moisture is a substudy in AFS, and there is no knowledge of whether the forest can limit the water content for crops [14].

The overall performance of a sustainable agricultural production system is reliant on obtaining large inputs of straw across the soil surface, and this can be accomplished by cultivating crops intercropped with cover crops [16]. The main crops used in the no-till system in the Cerrado region are soybeans (*Glycine max* (L.) Merrill); corn (*Zea mays* L.), cotton (*Gossypium hirsutum*), beans (*Phaseolus vulgaris* L.), sorghum (*Sorghum bicolor* L. Moench), sunflower (*Helianthus annuus* L.), and tropical forage grasses of the genus *Urochloa* sp. [1]. These crops can be grown alone or intercropped with a wide diversity of forest species, including eucalyptus (*Eucalyptus* spp.) [17].

The balance (storage/emission) of C in different cropping systems is more common in the Cerrado than in other biomes [18]. Pinheiro et al. [19] evaluated the C stock in different cropping systems in the Cerrado biome and observed that pastures accumulate significantly more C (260 Mg ha^{-1} m^{-1}) than eucalyptus plantations (174 Mg ha^{-1} m^{-1}) and native vegetation (167 Mg ha^{-1} m^{-1}). In addition, AFS systems improve the structural conditions of the soil, which favors most of the water infiltration in the soil, reduces surface runoff, and prevents erosion and pollution of surface water sources [20]. This increase in the water infiltration rate in the soil profile results in the development of larger and deeper roots, which increases the tillage explored by the root system and improves the efficiency of water and nutrient use by the agricultural crop [11]. However, the evaluated impact of crop systems on soil moisture and crop yields has rarely been studied in the Brazilian Cerrado.

In Brazil, the area occupied by the corn crop in the 2021/2022 harvest was 17.25 million hectares cultivated during the first harvest (spring–summer), which is sown from September to December and harvested from January to April, and the second harvest

(fall–winter), which is sown from January to March and harvested from May to August [21]. The off-season corn planted in the summer and harvested in the fall/winter occupies 71.6% of the area and has an average grain yield of approximately 5857 kg ha^{-1} [21]. Thus, most corn is grown in the off-season.

The high straw persistence, high dry matter production, good weed suppression efficiency and aggressive and deep roots are characteristic of *Urochloa*, which is why they are used as cover crops in the Brazilian cerrado, and furthermore, ruzigrass promotes nutrient cycling mainly of N [22].

This research aimed to evaluate changes in soil moisture content during the cultivation of soybean and off-season corn crops subjected to different soil management systems. In one study, we investigated the effect of center pivot irrigation management on the soil moisture and yield of soybean grown in the no-tillage system under ruzigrass (*Urochloa ruziziensis*) straw, and in another experiment, we evaluated the effect of intercropped and nonintercropped cultivation of corn with ruzigrass in an agricultural area with and without the influence of eucalyptus reforestation on the soil moisture content and yield of the off-season corn crop. Our hypothesis is that grain yield, 1000-grain mass production and soil moisture depend on the drought stress occurring during cultivation regardless of the type of soil management used.

2. Materials and Methods

2.1. Description of Study Locations

Two field experiments were conducted during the 2018–2019 growing season in deep clay soil, classified as Ferralsols [23] (Latossolo Vermelho distrófico under the Brazilian classification) with 54–58% clay and 36–39% sand in the municipality of Chapadão do Sul, Mato Grosso do Sul, Brazil (Figure 1). The first experiment was conducted in an irrigated area with a center pivot system located in the experimental field of Chapadão Agricultural Research Support Foundation—Chapadão Foundation (18°46′49″ S, 52°38′51″ W, and altitude of 810 m), and the impact of irrigation management on the soil moisture content and grain yield of soybean cultivars was investigated. The second experiment was carried out under rainfed conditions in the experimental area of the Federal University of Mato Grosso do Sul—UFMS (18°46′16″ S, 52°37′25″ W, and altitude of 810 m) and investigated the effect of conservation production systems on the soil moisture content and grain yield of off-season corn hybrids.



Figure 1. The location of the center pivot agricultural area was used to investigate irrigation management for soybean cultivation (Experiment 1), while the agricultural areas were named UFMS 1 and UFMS 2 (Experiment 2).

The regional weather, in agreement with Köppen's classification, is Aw, featured as tropical with hot summers and high rainfall rates and dry winters, with a drought station between May and September [24]. The average annual temperature is 24.1 °C, with a

minimum of 18.8 °C (July) and a maximum of 29.0 °C (January). The average annual rainfall ranges from 1600 to 1800 mm [24].

2.2. Experiment 1—Soybean Cultivars under Irrigation

In March 2018, ruzigrass (*Urochloa ruziziensis*) was manually sown at a density of 10.0 kg seeds ha^{-1} without the addition of mineral fertilizer [22]. The ruzigrass crop was cultivated to produce straw for subsequent soybean cultivation under a no-tillage system [22]. At 150 days after sowing, the ruzigrass plants were chemically desiccated with glyphosate (920 g ha^{-1} of the active ingredient) at a spray volume of 180 L ha^{-1} [22].

In September 2018, before soybean sowing, the soil of the experimental area was sampled in the 0.0–0.15 and 0.15–0.30 m layers, and the main physical-hydric properties are shown in Table 1. All soil physical characteristics were measured in accordance with the methods of the Brazilian Agricultural Research Corporation published by Teixeira et al. [25].

Table 1. Physical-hydric properties of the clayey Rhodic Hapludox in the center pivot agricultural area. Chapadão do Sul, MS, Brazil. 2018.

Depth	θfc	θpwp	AWC	BD	PD	TP	Soil Particle Size		
							Sand	Silt	Clay
m	$m^3\ m^{-3}$			$kg\ dm^{-3}$		$m^3\ m^{-3}$	$g\ kg^{-1}$		
0–0.15	0.413	0.282	0.131	1.34	2.65	0.536	392	67	541
0.15–0.30	0.383	0.262	0.121	1.44	2.65	0.484	368	45	587

θfc: volumetric soil moisture at field capacity measured at a matric potential (Ψm) of –30 kPa. θpwp: volumetric soil moisture at the permanent wilting point measured at a matric potential (Ψm) of −1500 kPa. AWC: available water capacity. BD: soil bulk density. PD: Soil particle density. TP: Soil total porosity.

The treatments were arranged as a split-split plot in a randomized complete block design with four replicates. In the main plots, two levels of ruzigrass straw remaining on the soil surface were established for the production system (1600 kg ha^{-1} (low straw level) and 6000 kg ha^{-1} of dry matter (high straw level)). The subplots were represented by applying three irrigation water levels (0, 50, and 100% of the crop evapotranspiration). The subsubplots were characterized by cultivating four soybean cultivars (NA 5909 RG, BMX Desafio RR, CD 2737 RR, and TMG 7067 IPRO). The experimental units consisted of five soybean rows that were 5.0 m long, with 0.45 m between rows. The useful area comprized the three central rows of each subsubplot, disregarding 1.0 m of each edge (i.e., 4.05 m^2).

On 25 September 2018, soybeans were mechanically sown at a depth of 3.0 cm in rows of 0.45 m and a density of 18 to 20 seeds per meter to reach a final stand of 400,000 to 450,000 plants per hectare [26]. Soybean fertilization was carried out as recommended by [27]. Fertilizer was applied by sowing 78 kg ha^{-1} of P_2O_5 and 16 kg ha^{-1} of N (monoammonium phosphate—MAP), and at 30 days after sowing (V_4 stage—four fully expanded leaves (fourth trifoliolate)), 80 kg ha^{-1} of K_2O (KCl) was applied in topdressing.

The soybean seeds used in this experiment were pretreated with pyraclostrobin + methyl thiophanate + fipronil (at a dose of 2 mL kg^{-1}) and then inoculated with efficient *Bradyrhizobium* spp. strains were used at a dose of 3.0 mL kg^{-1}, as recommended by the supplier.

The soybean cultivars used in this experiment are recommended for high-technology agricultural areas and have been largely planted in the Brazilian Cerrado region. A few of the agronomical features of the four soybean varieties used in this trial are displayed in Table 2. The management of the center pivot irrigation system used in this study was carried out based on the meteorological conditions during soybean crop development, following the methodology of Penman–Monteith-FAO, according to Allen et al. [28]. The meteorological data were obtained from the automatic meteorological station located approximately 200 m from the experimental area. Crop evapotranspiration (ETc) was estimated by the relationship between reference evapotranspiration (ET0) and crop coefficient (Kc).

Table 2. Some characteristics of the four soybean cultivars used in this experiment.

No	Cultivar	Maturity Cycle (Days)	Relative Maturity Group	Growth Habit	Soil Fertility Requirement
C01	NA 5909 RG	95–105	6.2	Indeterminate	High
C02	BMX DESAFIO RR	110–120	7.4	Indeterminate	High
C03	CD 2737 RR	105–115	7.3	Indeterminate	High
C04	TMG 7067 IPRO	110–115	7.2	Semidetermined	High

The water was only applied through the center pivot irrigation system when the water balance of the soybean crop was close to the lower limit of the soil's readily available water (RAW) (Figure 2). Thus, irrigation (50% and 100% of the ETC accumulated in the period) was only performed when the soybean plants consumed all the readily available water.

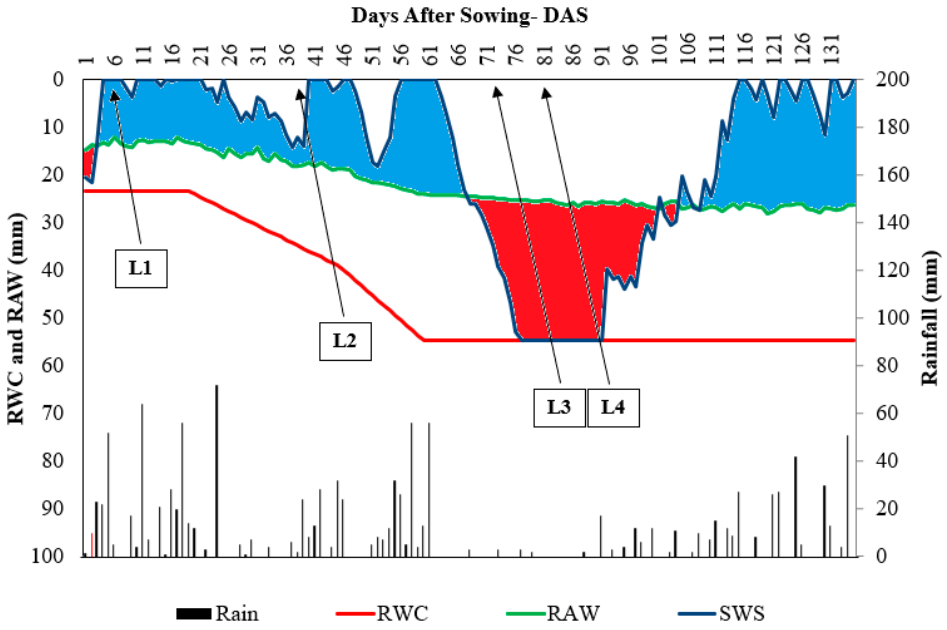


Figure 2. Soil water balance during soybean cultivation in rainfed conditions in a clayey soil of the Brazilian Cerrado in the 2018/2019 season. RWC: Residual water content. RAW: readily available water. SWS: soil water storage. The arrows indicate the dates of the volumetric soil moisture readings (R).

The volumetric soil moisture was measured using an electronic soil moisture meter, Hidrofarm model HFM 1010 (Falker®, Porto Alegre, RS, Brazil), at 0.20 m depth. Soil moisture readings (R) were performed on 29 September 2018 (R_1), 31 October 2018 (R_2), 5 December 2018 (R_3), and 12 December 2018 (R_4) during the vegetative and reproductive stages of the soybean crop (Figure 2). The recorded data were corrected for clayey soil, as recommended by Gava et al. [29].

Weed, pest and disease controls were conducted in compliance with the needs and technical advice of the soybean crop. At physiological maturity (R_8 stage), soybean cultivars were harvested, and then the 1000 sand-grain mass and grain yield were measured. All plants contained in 3.0 m of the three central rows of each plot were harvested mechanically, and the grains were cleaned and weighed. Grain yield was determined after grain weights were adjusted to a 13% moisture level. The 1000-grain mass was established by the average of eight 100-grain samples.

2.3. Experiment 2—Corn Hybrids under Conservation Agricultural Systems

In this study, the field trial consisted of the intercropped and nonintercropped cultivation of off-season corn with ruzigrass in two agricultural areas belonging to the Federal University of Mato Grosso do Sul, called UFMS 1 and UFMS 2, in Chapadão do Sul, MS,

Brazil (Figure 3). The agricultural production area called UFMS 1 is directly influenced by an area of eucalyptus reforestation located 8–10 m away on its northwest face. Therefore, as the proximity of the eucalyptus forest impacts the agricultural production of this area, this area of agricultural production was called the agroforestry system. The eucalyptus reforestation area consists of a 4-year-old *Eucalyptus urograndis* hybrid (*Eucalyptus grandis* × *Eucalyptus urophylla*) (clone AEC 1444) with an average height of 17.4 m. The experimental plots were arranged following the proximity of the lateral edge of the eucalyptus reforestation area. The production area called UFMS 2 was constituted by the traditional agricultural production system. This area is 150 m from the UFMS 1 area and is not influenced by the eucalyptus forest (Figure 3).

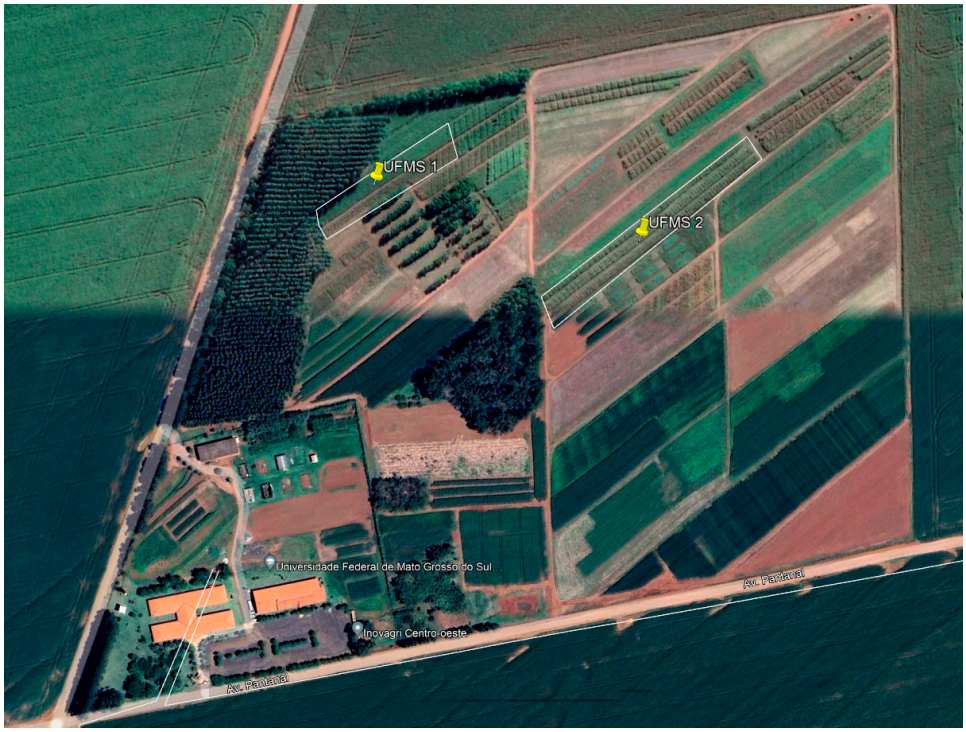


Figure 3. Location of the two experimental trials conducted in the agricultural production areas named UFMS 1 and UFMS 2 in Chapadão do Sul, MS, Brazil, during the 2019 off-season.

The treatments were arranged as a split-split plot in a randomized complete block design with four replicates. The main plots consisted of two production systems (agricultural area with (agroforestry system—UFMS 1) and without (traditional system—UFMS 2) direct effect of the eucalyptus forest). The subplots consisted of intercropped and nonintercropped corn with ruzigrass. The subsubplots were represented by the cultivation of two corn hybrids (NS50 RR2 PRO PRO2 (simples hybrid, super early cycle of 130–142 days and high yield potential) and INVICTUS VIP3 (simples hybrid, early cycle of 140–150 days and high yield potential)). The trial units (subplot) comprized seven corn rows, with 0.45 m interrow spacing and 5 m in length (15.75 m^2). The utility area comprized the five central rows of each subplot, ignoring 0.5 m from each edge (i.e., 9.0 m^2).

The corn crop was mechanically sown on 8 February 2019, at a depth of 3.0 cm in rows of 0.45 m and a density of 3 seeds per meter to reach a final stand of 55,000 to 60,000 plants per hectare [30]. Corn seeds were previously treated with 150 g kg^{-1} imidacloprid and 450 g kg^{-1} thiodicarb [30]. Corn fertilization was carried out as recommended by [27]. Fertilization was carried out by applying 104 kg ha^{-1} of P_2O_5 and 22 kg ha^{-1} of N (monoammonium phosphate—MAP) at sowing. At 35 days after emergence—DAE (V_5 stage—five fully expanded leaves), 120 kg ha^{-1} of N (urea) and 90 kg ha^{-1} of K_2O (KCl)

were applied in topdressing. At 40 DAE (V_6—six fully expanded leaves), foliar fertilization was applied using 1 L ha^{-1} of Actilase ZM (50 g L^{-1} Zn; 42 g L^{-1} S; 30 g L^{-1} Mn).

Ruzigrass (*Urochloa ruziziensis* (R. Germ. and C.M. Evrard) Crins) was sown simultaneously with the corn crop in a seeder-fertilizer machine with a double-disc furrow mechanism for no-till [16]. The seeds were sown at a depth of 5.0 cm at a spacing of 22 cm, using 5 kg ha^{-1} of 64% viable seed, as advised by Ceccon et al. [31].

Weed control was performed at 20 DAE of corn plants using 2.0 L ha^{-1} atrazine. To retard the growth of ruzigrass plants, nicosulfuron was applied at a dose of 8 g ha^{-1}, as advised by Ceccon et al. [31]. All herbicide applications were performed with mineral oil 0.5% (v:v). At the beginning of corn flowering, the fungicides pyraclostrobin and epoxiconazole were applied at rates of 100 and 88 g a.i. ha^{-1}, respectively. The insecticides metomil, imidacloprid, and thiodicarb were also applied at doses of 13, 45, and 135 g a.i. ha^{-1}, respectively. Weed, pest, and disease controls were carried out according to the needs and technical recommendations of the corn crop. During the development of the off-season corn crop, the volumetric soil moisture was measured using an electronic soil moisture meter, Hidrofarm model HFM 1010 (Falker®), at 0.20 m depth. Soil moisture readings (R) were performed on 21 February 2019 (R_1), 8 March 2019 (R_2), 8 April 2019 (R_3), 22 April 2019 (R_4) and 21 May 2019 (R_5) during the vegetative and reproductive stages of the corn crop (Figure 4). The recorded data were corrected for clayey soil, as recommended by Gava et al. [29].

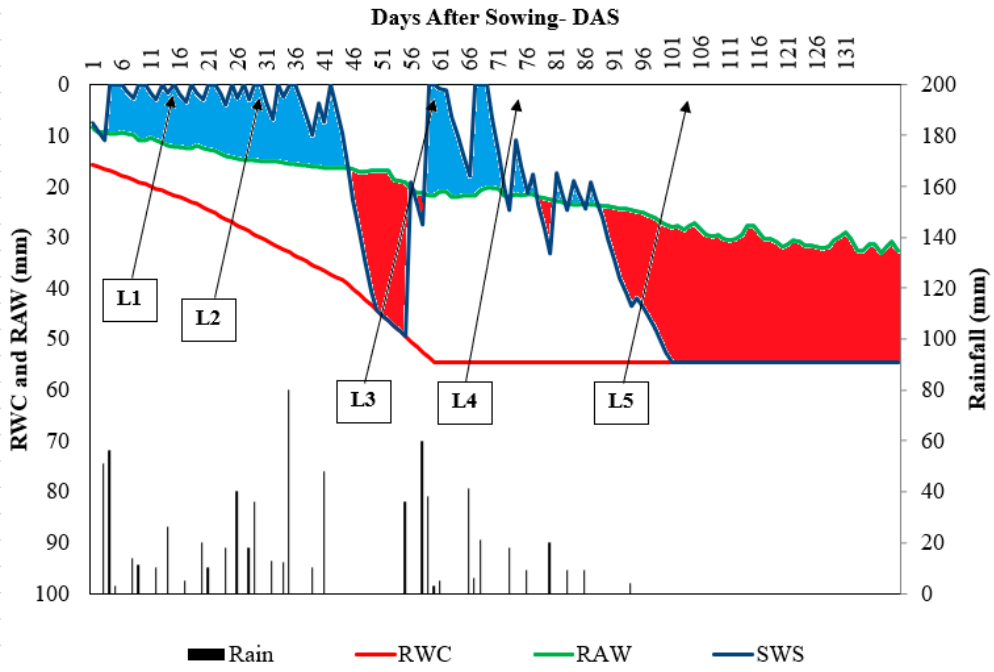


Figure 4. Soil water balance during off-season corn cultivation in rainfed conditions in a clayey soil of the Brazilian Cerrado in the 2019 season. RWC: Residual water content. RAW: readily available water. SWS: soil water storage. The arrows indicate the dates of the volumetric soil moisture readings (R).

At physiological maturity (R_6 stage), corn hybrids were harvested, and then 1000-grain mass and grain yield were measured. All ears of corn in the plot's effective area were harvested by hand and then threshed in a Wintersteiger Classic® Harvester. The kernels were cleaned and weighed, and grain yield (kg ha^{-1}) was estimated after correcting the grain weight to 13% moisture. The 1000-grain mass was determined by averaging eight measurements of 100 grains.

2.4. Statistical Analysis

The data were subjected to analysis of variance by the F test at the 5%, 1%, and 0.1% probability levels using Rbio software, version 01, for Windows [32]. The treatment means were compared by Tukey's test at the 5% probability level when significant.

3. Results

3.1. Effects of Irrigation Management on the Soil Moisture Content and Grain Yield of Soybean Cultivars

Reading time and irrigation management significantly affected soil moisture, and the thousand-grain mass and soybean yield were significantly influenced by soybean cultivar genetic variability (Table 3). Changes in soil moisture content occurred due to soil water balance (Figure 2) and water applied by the center pivot irrigation system.

Table 3. Summary of analysis of variance for soil moisture content, thousand-grain mass, and soybean grain yield in response to soil moisture reading times, ruzigrass straw level on the soil surface, irrigation system management, and soybean cultivar.

Causes of Variation	Soil Moisture Content	Thousand-Grain Mass	Grain Yield
Block	2.59 ^{NS}	0.27 ^{NS}	0.95 ^{NS}
Reading times (R)	32.64 ***	–	–
Straw level (S)	0.34 ^{NS}	0.01 ^{NS}	0.01 ^{NS}
Irrigation (I)	37.96 ***	1.36 ^{NS}	3.21 ^{NS}
Soybean Cultivar (C)	1.91 ^{NS}	11.79 ***	3.37 *
R × S	1.15 ^{NS}	–	–
R × I	22.97 ***	–	–
R × C	1.70 ^{NS}	–	–
S × I	1.59 ^{NS}	0.33 ^{NS}	0.28 ^{NS}
S × C	1.81 ^{NS}	0.18 ^{NS}	2.40 *
I × C	0.23 ^{NS}	0.42 ^{NS}	1.16 ^{NS}
R × S × I	0.36 ^{NS}	–	–
R × S × C	0.67 ^{NS}	–	–
R × I × C	0.90 ^{NS}	–	–
S × I × C	1.00 ^{NS}	0.45 ^{NS}	0.30 ^{NS}
R × S × I × C	0.70 ^{NS}	–	–
CV (%)	21.03	20.29	36.70

NS: not significant. *, and ***: Significant at 5%, 1% and 0.1%, respectively.

The level of ruzigrass straw on the soil surface at soybean sowing did not significantly affect the soil moisture content (Table 3). The higher soil moisture content observed in the fourth reading (R_4) was due to the irrigation applied between the third (5 December 2018) and fourth (12 December 2018) reading intervals (Figure 5).

Cultivars NA 5909 RG and TMG 7067 IPRO had a higher thousand-grain mass than cultivars BMX DESAFIO RR and CD 2737 RR (Figure 6A). However, soybean cultivars have similar grain yields when grown in a no-tillage system under low and high levels of signal grass straw on the soil surface (Figure 6B).

3.2. Effects of Conservation Production Systems on the Soil Moisture Content and Grain Yield of Off-Season Corn Hybrids

The soil moisture content during the off-season corn development phases varied with the reading times and the agricultural production system; however, there was no significant interaction between these factors (Table 4). The intercropping and nonintercropping of corn with ruzigrass and the use of corn hybrids did not have a significant effect on soil moisture content. The corn hybrids had a significant effect on the thousand-grain mass. There was a triple interaction between agricultural production systems, intercropped and nonintercropped cultivation of corn with signal grass and corn hybrid for grain yield (Table 4).

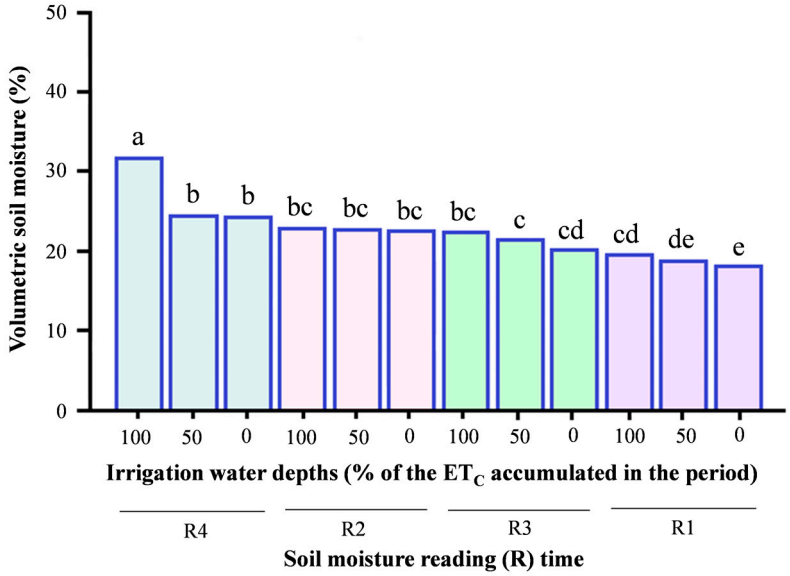


Figure 5. The soil moisture content was measured during the developmental stages of soybean grown under different irrigation conditions. R_1, R_2, R_3, and R_4 represent the soil moisture readings performed on 29 September, 31 October, 5 December, and 12 December 2018, respectively. Bars followed by distinct letters show significant differences by Tukey's test ($p < 0.05$).

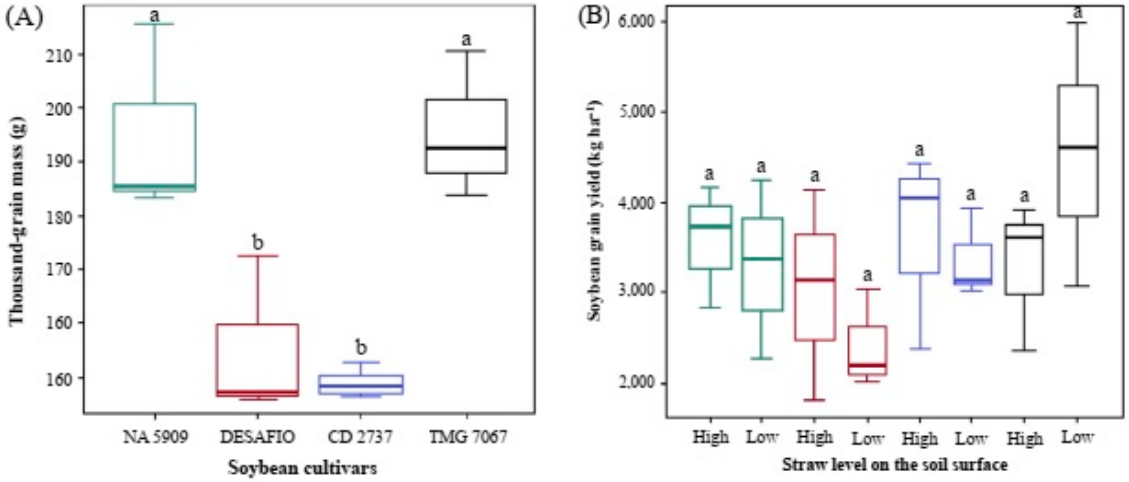


Figure 6. Thousand-grain mass (**A**) and grain yield (**B**) of the four soybean cultivars grown in clayey soil in the Brazilian Cerrado under a no-tillage system with high (6000 kg ha^{-1}) and low (1600 kg ha^{-1}) levels of ruzigrass straw on the soil surface. Green, red, blue, and black boxplots represent soybean cultivars NA 5909 RG, BMX DESAFIO RR, CD 2737 RR, and TMG 7067 IPRO, respectively. Bars followed by distinct letters show significant differences by Tukey's test ($p < 0.05$).

The soil moisture content was significantly higher in the first reading (R_1) performed at the beginning of the off-season corn crop development (Figure 7A). The higher soil moisture was due to the greater availability of water in the soil measured through the soil water balance (Figure 4). Subsequently, with the development of the corn crop, there was a decrease in soil moisture content, as observed in the second (R_2) and third (R_3) readings. The lowest soil moisture content was obtained in the fourth (R_4) and fifth (R_5) readings. The agroforestry system under eucalyptus reforestation resulted in the highest soil moisture content compared to the traditional production system (Figure 7B).

Table 4. Summary of analysis of variance for soil moisture content, thousand-grain mass, and corn grain yield in response to soil moisture reading times, agricultural production systems (agroforestry and traditional system), intercropped and nonintercropped cultivation of corn with ruziziensis and corn hybrids.

Causes of Variation	Soil Moisture Content	Thousand-Grain Mass	Grain Yield
		F value	
Block	2.93 ^{NS}	8.69 ^{NS}	32.16 **
Reading times (R)	80.64 ***	–	–
Production system (S)	7.71 **	0.07 ^{NS}	1.48 ^{NS}
Intercropped cultivation (I)	0.02 ^{NS}	0.49 ^{NS}	0.26 ^{NS}
Corn hybrid (H)	2.33 ^{NS}	3.64 *	1.20 ^{NS}
R × S	1.96 ^{NS}	–	–
R × I	1.47 ^{NS}	–	–
R × H	0.43 ^{NS}	–	–
S × I	1.88 ^{NS}	4.17 ^{NS}	4.43 ^{NS}
S × H	0.68 ^{NS}	0.24 ^{NS}	0.39 ^{NS}
I × H	1.85 ^{NS}	0.08 ^{NS}	0.74 ^{NS}
R × S × I	1.36 ^{NS}	–	–
R × S × H	0.55 ^{NS}	–	–
R × I ×H	1.29 ^{NS}	–	–
S × I × H	0.03 ^{NS}	0.06 ^{NS}	5.79 **
R × S × I × H	0.73 ^{NS}	–	–
CV (%)	16.24	21.15	30.80

NS: not significant. *, ** and ***: Significant at 5%, 1% and 0.1%, respectively.

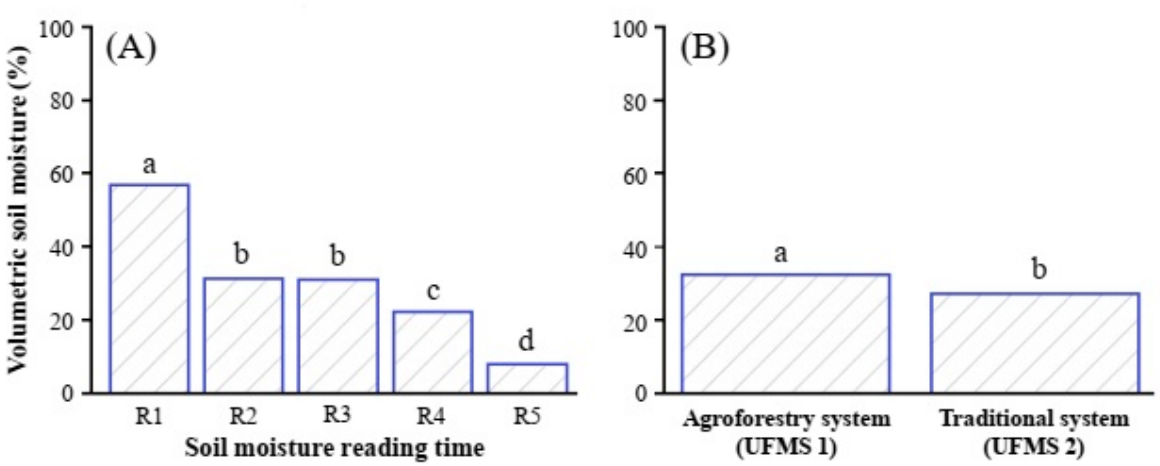


Figure 7. Soil moisture content measured during the developmental stages of off-season corn crop grown in two agricultural production systems (agricultural area with (agroforestry system—UFMS 1) and without (traditional system—UFMS 2) direct effect of the eucalyptus forest) in Chapadão do Sul, MS, Brazil during the 2019 growing season. R_1, R_2, R_3, R_4, and R_5 represent the soil moisture readings performed on 21 February, 8 March, 8 April, 22 April, and 21 May 2019, respectively. Bars followed by distinct letters show significant differences by Tukey's test ($p < 0.05$). Corn crop development (**A**). Traditional production system (**B**).

The NS50 RR2 PRO PRO2 corn hybrid had a higher thousand-grain mass than the INVICTUS VIP3 hybrid (Figure 8A). However, corn grain yield was not significantly affected by agricultural production systems (agroforestry or traditional system) or by intercropped or nonintercropped cultivation of corn with ruzigrass (Figure 8B).

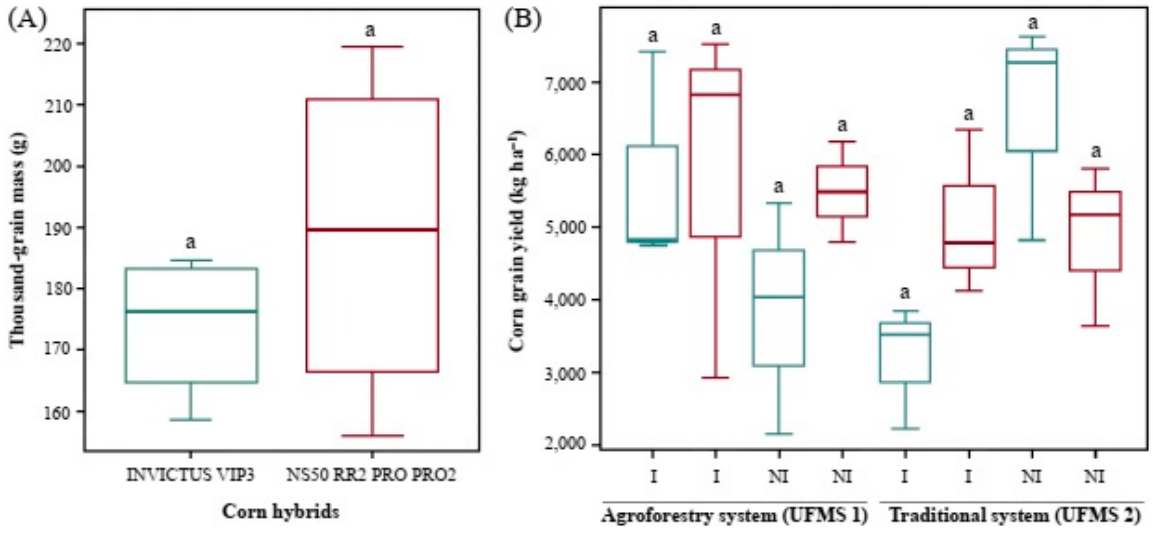


Figure 8. Thousand-grain mass (**A**) and grain yield (**B**) of the two off-season corn hybrids grown in intercropped (I) and nonintercropped (NI) systems with ruzigrass under different production systems [agricultural area with (agroforestry system—UFMS 1) and without (traditional system—UFMS 2) direct effect of the eucalyptus forest] in Chapadão do Sul, MS, Brazil during the 2019 growing season. Green and red boxplots represent corn hybrids INVICTUS VIP3 and NS50 RR2 PRO PRO2, respectively. Bars followed by distinct letters show significant differences by Tukey's test ($p < 0.05$).

4. Discussion

4.1. Effects of Irrigation Management on the Soil Moisture Content and Grain Yield of Soybean Cultivars

We expected higher soil moisture at higher ruzigrass straw levels (6000 kg ha^{-1}) in irrigated and nonirrigated systems during soybean cultivation. However, using a meta-analysis, Wang et al. [33] showed that the use of cover crops increased soil water storage at a depth of 30 cm. Alfonso et al. [34] related that evapotranspiration in soybeans following cover cropping was reduced, and water productivity was increased compared to the system without cover crops.

The water supply to the agricultural production system in the soil, either through natural processes such as rainfall or through irrigation, increases the moisture content of the soil [9]. In this context, it is noted that the soil moisture content was higher after irrigation with a water depth of 100% of the crop evapotranspiration (ETC) accumulated in the period (Figure 2). The sensor was efficient in monitoring changes in soil moisture content promoted by different irrigation water management practices, confirming the findings of Gava et al. [29]. Sperandio et al. [8] reported that they obtained an excellent correlation between gravimetric soil water content and soil moisture measured by sensors, and the soil moisture content may vary with the rainfall and drought season.

The water requirement of the soybean crop increases in the flowering and grain-filing stages and may require 450 to 850 mm during its development cycle [26]. Thus, the negative soil water balance observed during the flowering and filling phases of soybean grains (Figure 2) resulted in the lowest grain yield of soybean cultivars. However, the application of irrigation water during the third (R_3) and fourth (R_4) readings of soil moisture content increased soil water availability and decreased plant water restriction, especially with a water depth of 100% of the crop evapotranspiration. On the other hand, even with irrigation of 100% of evapotranspiration, there was no increase in soybean grain yield compared to hydric restriction. Silva et al. [35] described that they could reduce the crop coefficient (Kc) of soybean to determine the hydric need of soybean due to the ability of soybean to close the stomata and decrease evapotranspiration and its adaptation to the soil and climate conditions of Brazil. The grain yield of soybean cultivars depends on

the genetic potential and the conditions of the agricultural production environment [36]. Grain yield potential and thousand-grain mass are intrinsic characteristics of each soybean genotype and/or cultivar [37]. The agriculture practices prati and the irrigated cultivation system play a role in the dissimilarity of soybean cultivars [38,39]. However, we did not observe any distinction in the yield of soybean cultivars evaluated as a function of irrigation and the practice of increasing the straw of the ruzigrass in no-till systems. The lack of genotypic divergence among soybean cultivars may have occurred due to their ability to adapt to regional growing conditions [40]. Climate change can promote more intense drought stress in tropical regions, decreasing soybean production due to the low water content in the soil, and we must seek management alternatives that do not promote grain production [41]. However, we observed that irrigation and the use of ground cover (ruzigrass) were not sufficient to promote the yield of soybean in a water-stressed environment during cultivation.

4.2. Effects on the Soil Moisture Content and Grain Yield of Off-Season Corn Hybrids

The soil water restriction observed in the last soil moisture readings corresponded to the lowest rate of rainfall that occurs from April onward in the Brazilian cerrado region [4]. Thus, the climatic conditions during off-season corn cultivation were decisive for the soil moisture content, which is consistent with the moisture sensor readings [42]. The use of moisture sensors can be a practical tool to indicate the need for irrigation or to observe hydric restriction conditions during the cultivation of corn [43].

The agroforestry system under eucalyptus reforestation resulted in the highest soil moisture content compared to the traditional production system. We observed that drought stress for corn plants can be ameliorated in agroforestry, especially in the afternoon, because of the shading of the corn crop caused by eucalyptus trees. According to Peng et al. [44], the reforestation area increased the relative humidity by 7% and reduced the ambient temperature by 1.2 °C during soybean cultivation, and these environmental effects had a direct impact on improving soil water availability. Campanha et al. [45] showed that the agroforestry system has the highest soil moisture content.

On the other hand, it was expected that the proximity to eucalyptus would increase the water depletion in the soil for corn plants [14]. Schume et al. [46] observed that soil water depletion is higher at the edge of a forested corn field (6 m) but did not differ in soil water content from single corn fields (30 m away from the corn). Mugunga et al. [47] also reported soil water depletion in maize growing close to eucalyptus in an AFS. Thus, there is no consensus that the use of eucalyptus is detrimental to the cultivation of corn in AFSs because the development of corn can be favored or hindered by the soil and climate conditions of each region.

Bertalot et al. [48] reported that the thousand-grain mass and grain yield of maize were not significantly affected by cultivation in AFS with Leucena trees (*Leucaena diversifolia* (Schltdl.) Benth.). Nyaga et al. [14] showed that AFS promoted corn yield when using *Caliandra macrostachyus* trees, a leguminous species, compared to nonleguminous plants such as *Eucalyptus* spp. However, similar results were observed in our study for corn cultivation in AFS using *Eucalyptus* spp. Thus, under suitable climatic conditions, the yield of corn crops in AFSs with eucalyptus trees may be less affected than expected.

In our study, corn hybrids were not affected by the use of *Urochloa ruziziensis* in agroforestry and no-till systems. The intercropping of *Urochloa ruziziensis* with corn results in greater straw production, greater soil coverage and greater nutrient cycling, maintaining a higher quality soil in the no-till system without reducing the productive potential of corn [49–51]. Therefore, other long-term experiments should be conducted to evaluate the impact of the agroforestry system on the yield potential of off-season corn crops grown in intercropped and nonintercropped systems with ruzigrass.

5. Conclusions

Soil moisture content is inherent to the soil and climatic conditions of the region and can be altered by irrigation and the effect of the eucalyptus forest. Interharvesting corn with ruzigrass did not alter the soil moisture content. The soybean cultivars NA5909 and TMG7067 had higher soybean mass in a no-till system with center pivot irrigation; however, irrigation water did not improve soybean yield. Off-season corn hybrids have no genetic divergence in yield potential when grown in crop production systems under eucalyptus forest areas or intercropped with ruzigrass.

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