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Sunflower root growth and distribution under varied water regimes in two edaphoclimatic conditions

Luis Henrique Loose[1*], Arno Bernardo Heldwein[2], Jocélia Rosa da Silva[3], Mateus Leonardi[2], Mateus Possebon Bortoluzzi[4] and Dionéia Daiane Pitol Lucas[2]

[1] Instituto Instituto Federal de Educação Ciência e Tecnologia Farroupilha, Campus Santo Ângelo, Rodovia RS 218, km 5, Indubrás, 98806-700, Santo Ângelo, Rio Grande do Sul, Brazil. [2]Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brazil. [3]Irriga Global, Santa Maria, Rio Grande do Sul, Brazil. [4]Universidade de Passo Fundo, Passo Fundo, Rio Grande do Sul, Brazil. *Author for correspondence. E-mail: luis.loose@iffarroupilha.edu.br

ABSTRACT. Sunflower growth is adversely impacted by both excess and insufficient water. Research on root growth in this crop under water stress conditions remains limited and does not fully elucidate the plant's response to varying soil and climatic conditions. This study aimed to determine root growth, depth, and distribution of sunflower plants under different water stress conditions, such as deficit or excess, in two soil classes and sown during two distinct periods. Experiments were conducted after sowing at the beginning of September (first crop season) and at the beginning of January (second crop season) in an Ultisol (Santa Maria, Rio Grande do Sul State, Brazil) and an Oxisol (Panambi, Rio Grande do Sul State, Brazil). Water condition treatments applied from stage V6 included control, water deficit, and water excess. Roots were collected using an auger drill during the first crop season. The variables analyzed comprised root length density and accumulated root within the soil profile. During the second crop season, sunflower roots were visually assessed in the soil profile after trench excavation. Root system depth and root dry mass were evaluated during both sowing periods. Results indicated that sunflower root penetration is deeper in Ultisol than in Oxisol. Water deficit promotes root depth, while water excess promotes root growth near the surface. Sowing during the first crop season results in deeper root penetration and higher root dry mass production compared to the second crop season.

Keywords: *Helianthus annuus* L.; water excess; water deficit; sowing time.

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Introduction

Sunflower is an oilseed crop grown globally for its use in edible oil production, the pharmaceutical industry, animal feed, and biodiesel production. Although not among the most popular crops in Brazil, where annual grasses and leguminous crops dominate, sunflower serves as an alternative for crop rotation systems. Water stress and diseases are the primary factors contributing to yield reduction in this crop (Loose, Heldwein, Silva, & Bortoluzzi, 2019; Brand et al., 2020), with a national average yield of approximately 1,143 kg ha^{-1} (Companhia Nacional de Abastecimento [CONAB], 2022). Such a stress leads to morphophysiological changes in cultivated plants as they adapt to new conditions (Loose et al., 2019; Ni et al. 2019; Masalia, Temme, Torralba, & Burke, 2018). This adaptive capability is called phenotypic plasticity and allows plants to respond to environmental fluctuations (Sadras, Hall, Trapani, & Vilella, 1989).

Water is vital for plant physiological processes such as photosynthesis, nutrient and metabolite transport, heat dissipation, and turgidity maintenance. Consequently, water deficit is a primary limitation to plant biomass production (Taiz, Zeiger, Møller, & Murph, 2017). Among plant responses to this stress, root deepening is a general way to overcome it (Sharp et al., 2004; Masalia et al., 2018), as plants can access deeper soil layers with higher water availability.

The primary roots of many plant species can penetrate soil even under water potential values lower than -1.5 MPa, while shoot and secondary root growth are suppressed earlier (Sharp et al., 2004). Kage, Kochler, and Stützel (2004) argued that additional energy is required to deepen the root system at the expense of shoot growth. Therefore, the later the onset of water deficit occurs before anthesis, the lower the plant's capacity to morphologically adapt to such a condition (Asseng, Ritchie, Smucker, & Robertson, 1998).

Conversely, during water excess, seminal root growth can halt within hours after soil waterlogging, leading to root senescence in sunflower crops (Grassini, Indaco, Pereira, Hall, & Trápani, 2007; Loose et al., 2017). Hence, plants begin producing adventitious and secondary roots near the soil surface. This capacity to generate new roots to replace suffocated ones is a plant response developed to tolerate water excess (Loose et al., 2017).

These above-mentioned responses are driven by plant hormones. Cytokinins promote primary root penetration, while auxins enhance secondary root growth (Aloni, Aloni, Langhans, & Ullrich, 2006). Abscisic acid may inhibit secondary root growth (Xiong, Wang, Mao, & Koczan, 2006), and ethylene gas encourages the formation of adventitious and secondary roots and participates in the senescence of suffocated root tissues (Acharya & Assmann, 2009).

Both stress types reduce biomass accumulation in sunflower plants, alter the shoot/root ratio, and decrease leaf area and shoot growth under water deficit (Soares et al., 2019; Kage et al., 2004) or water excess conditions (Paul et al., 2021). Thus, understanding plant responses to these conditions is crucial to mitigate losses caused by water stress.

Roots are the first organs affected by extreme water conditions, and studies evaluating sunflower root growth under field conditions remain scarce. Connor and Sadras (1992) asserted that sunflower roots can penetrate deeper into the soil than other crops, such as maize, soybean, and sorghum, reaching soil depths of up to 2.0 m. Rauf and Sadaqat (2007) reported root depth values of up to 1.8 m for a sunflower cultivar. However, these studies were conducted in soils with low clay content from Mediterranean regions.

Rigorous scientific investigation is essential for assessing the growth, penetration, and distribution of sunflower roots in response to stress caused by water deficit and excess, particularly when plants are grown in soils with high clay contents. Therefore, this study aimed to evaluate the root growth, penetration, and distribution of sunflower plants cultivated under stress conditions induced by water deficit or excess in an Ultisol and an Oxisol in the state of Rio Grande do Sul, Brazil.

Material and methods

The experiments were conducted in the experimental area of the Plant Science Department of the Federal University of Santa Maria (UFSM), located in the municipality of Santa Maria, Central Depression Region of Rio Grande do Sul (RS) State, Brazil - (latitude 29°43'23" S, longitude 53°43'15" W, and elevation of 95 m); and in the municipality of Panambi, Middle Plateau Region of Rio Grande do Sul State, Brazil - (latitude 28°16'02" S, longitude 53°34'43" W, and elevation of 419 m) (Figure 1). The climate in both regions is classified as Cfa, according to Köppen's classification, characterized as humid subtropical without a defined dry season and with hot summers (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013). The soil in the experimental area of Santa Maria is an Ultisol with sandy texture in the first 0.50 m, with a textural B horizon below this level. The soil in the Panambi experimental area is an Oxisol with a highly clayey B horizon.

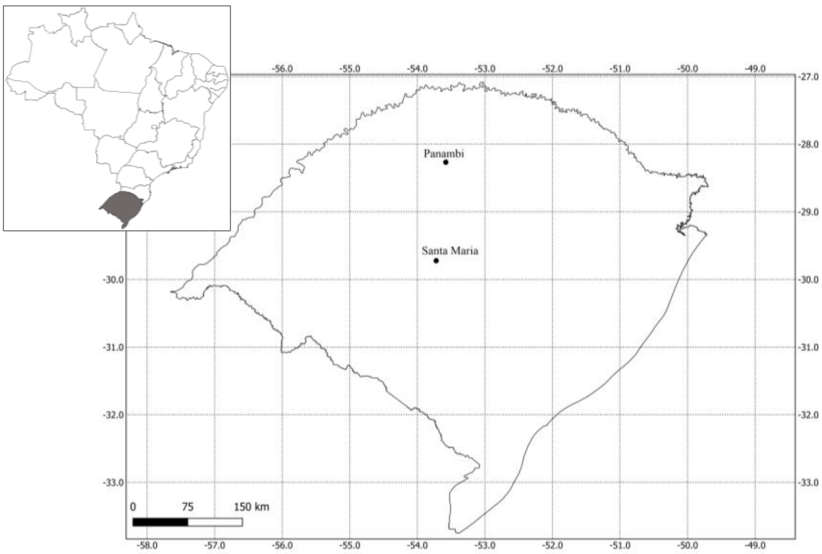

Figure 1. Map of the Rio Grande do Sul State (RS). Solid circles represent the locations of experimental areas. The inset map shows the location of RS within Brazil.

The experimental areas underwent soil correction in the previous autumn through NPK fertilization and liming. NPK was incorporated into the first 40 cm of the soil profile via subsoiling and light harrowing, along with simultaneous white oat sowing. Sunflower sowing during the first crop season was carried out after the desiccation of the oat crop, using the early sunflower hybrid Helio 250, which is recommended for the entire Brazilian territory. Fertilization with 300 kg ha^{-1} of NPK (5-20-20) and 30 kg ha^{-1} of Borax was conducted at sowing, and 220 kg ha^{-1} of urea was applied as topdressing at the phenological stage V10 (Schneiter & Miller, 1981), following the soil chemical analysis.

Sunflower seeds were directly sown into planting rows spaced 0.5 m apart. After thinning, the distance between plants in the rows reached 0.45 m, resulting in a total population of 44,444 plants ha^{-1}. This spacing was established to optimize plant arrangement in the area, facilitating root collection and minimizing damage to the roots of neighboring plants. Plant sampling was conducted in their respective plots, each covering 22 m^2.

The experiment was conducted at two locations, with two sowing dates, and under three soil water condition treatments. Sowing took place at the beginning of September (first crop season) and at the beginning of January (second crop season) in both soils (Ultisol and Oxisol). The water condition treatments included water deficit, water excess (rainfall plus irrigation above the maximum crop evapotranspiration (ETc) to reach saturation), and a control treatment (rainfall and irrigation equal to the ETc). A randomized block design was employed with four replications, resulting in a tri-factorial experiment (3 x 2 x 2). Factors referred to three soil water conditions, two sowing times, and two edaphoclimatic conditions.

Soil water conditions comprised the following treatments: control, in which optimal water availability conditions were provided to the plants to avoid water excess or deficit, maintaining water storage between 75 and 100% of the available water holding capacity (WHC); water deficit, with irrigation below crop requirements, maintaining water storage between 40 and 60% of WHC; and water excess, characterized by excess irrigation, maintaining water storage above 90% of WHC, where irrigation continued until soil saturation (167 mm in the Ultisol, and 144 mm in the Oxisol). Accordingly, each time the treatments reached the lower storage limit (40%, 75%, and 90%), the soil was irrigated until the upper storage limit (60%, 100%, and the saturation point). These water level conditions were based on the results recorded for the maize crop (Bergonci, Bergamaschi, Santos, França, & Radin, 2001). The treatments were applied from stage V6 onwards.

Cumulative thermal time was determined using three cardinal temperatures, considering the base temperature for the sunflower crop (4.2°C) (Sentelhas, Nogueira, Pedro Júnior, & Santos, 1994) as well as the optimum temperature (27°C) and the upper base temperature (34°C) (Maldaner et al., 2018).

The daily sequential water balance (Pereira, 2005) was adopted to determine soil moisture and the timing and amount of irrigation. An initial WHC (WHCin) was set at 0.10 m depth, along with a final WHC (WHCf) at 0.60 m depth. The WHC was calculated daily according to the thermal time and the equation proposed by Dourado-Neto, García y García, Fancelli, Frizzone, and Reichardt (1999), as follows:

$$WHCn = WWC_{in} + \left(\frac{WHC_f - WHC_{in}}{2}\right)\left\{1 - cos\left[\left(\pi^{\left(\frac{1}{F}\right)}.\frac{TT_{(n)}}{TT}\right)^F\right]\right\} \quad (1)$$

wherein: $TT_{(n)}$ is the cumulative thermal time until the day ‘n,’ in ºC day^{-1}; TT is the cumulative thermal time required to reach WHCf, in ºC day^{-1}; F is the exponential coefficient, which is 0.80 for sunflower; WHCin is the initial water holding capacity at 0.10 m depth, in mm; WHCf is the final water holding capacity at 0.60 m depth, in mm; and WHCn is the water holding capacity on day ‘n,’ in mm.

Reference evapotranspiration (ETo) was calculated using the Penman-Monteith method by adjusting the rate of solar radiation for longwave radiation as proposed by Righi, Heldwein, Maldaner, Lucas, and Stüker (2015). The crop coefficient (Kc) values recommended by FAO for the sunflower crop were used to calculate crop evapotranspiration (ETc) (Allen, Pereira, Raes, & Smith, 1998).

Meteorological data were collected by automatic weather stations belonging to INMET, which are in the municipalities of Santa Maria (60 m from the experimental area) and Cruz Alta (the nearest station to the Panambi experimental area: 45 km). Rainfall data were collected in the experimental areas using rain gauges.

The area designated for water deficit treatment was enclosed by a wooden structure similar to a Quonset-type greenhouse. To prevent soil moisture levels from rising above 60% WHC, the structure was covered with a low-density polyethylene film (LDPE) prior to each rain event. The film was then removed after the rain had stopped. To improve drainage and reduce the risk of water entering the system through subsurface lateral flow, trenches (0.3 m deep) were dug around the area. For irrigation, dripping tubes were installed between the planting rows.

At both locations and sowing times, root depth and dry mass were determined at stage R6. Additionally, during the first crop season, root distribution in the soil profile was assessed using the auger method employed by Kage et al. (2004) and Pivetta, Castoldi, Santos, and Rosolem (2011). We collected roots and soil samples at 0.0, 0.12, and 0.24 m distances from the reference plant (with a row distance of 0.50 m), and sampled soil layers every 0.1 m depth until no more roots were found. The roots were separated from the soil using a sieve, and the root length was measured to determine the root length density (RLD). We also determined the root percentage in the different soil layers by assessing the accumulated root variable in depth.

Throughout the second crop season, we visually assessed the root system and measured its depth by opening trenches and sampling four plants per treatment, following the procedure described by Böhm (1979). This was done at stage R6, during the plants' anthesis. The results were analyzed by variance analysis and means compared using Tukey's test ($p < 0.05$).

Results and discussion

The root dry mass at stage R6 did not show a significant interaction or difference between the two edaphoclimatic conditions, but it did exhibit a significant difference between water condition treatments and sowing times (Table 1). Plants grown under the control treatment had the highest values of root dry mass, while those treated with excess water showed a significant decrease. The plants under water deficit had the lowest values of root dry mass.

Root dry mass was higher in the first than in the second season, showing an overall 23% reduction. These results suggest that water deficit conditions lead to significant root biomass reduction compared to the control treatment. Kuster, Arend, Günthardt-Goerg, and Schulin (2013) stated that this is a plausible result since water deficit promotes primary root penetration and drastically reduces secondary root formation. Soares et al. (2019) also observed this reduction in root biomass in sunflower plants grown under water deficit conditions, which was intensified by weed competition.

Table 1. Root dry mass and depth at stage R6 of sunflower plants grown in the first (sown on September 6 and 7) and second (sown on January 6 and 7) crop seasons in Ultisol (Santa Maria/RS) and Oxisol (Panambi/RS) soils under control (Cont.), water excess (Exc.), and water deficit (Def.) treatments.

Root Dry Mass (g m^{-2})		**Root Depth (cm)			
Water Cond.	Mean	Water Cond.	First Crop Season		
			Ult.	Oxi.	Mean
*Cont.	112.07 a	Cont.	89.0 a	69.5 b	
Exc.	88.27 b	Exc.	70.5 b	41.0 c	76.1 a
Def.	61.08 c	Def.	98.2 a	88.4 a	
Season	Mean	Water Cond.	Second Crop Season		
			Ult.	Oxi.	Mean
First Crop Season	100.1 a	Cont.	55.0 a	55.0 a	
Second Crop Season	76.6 b	Exc.	47.5 a	32.5 b	53.8 b
-	-	Def.	75.0 b	57.5 a	
Mean	87.2	Mean	72.5 A	57.3 B	
CV (%)	29.0	CV (%)		11.5	

*Means followed by the same letter do not differ from each other in the column (lowercase letter) and in the row (uppercase letter) by Tukey's test ($p < 0.05$). ** Significant interaction between the three factors. Treatments: control (soil moisture between 75% and 100% WHC); water excess (soil moisture between 90% WHC and the determined irrigation point); water deficit (soil moisture between 40% and 60% WHC).

Differences in root dry mass between sowing times can be attributed to lower plant growth during the second crop season. At the start of this second season, high atmospheric water demands may have led to stress conditions earlier than in the first season, reducing CO2 assimilation and stomatal conductance (Ghobadi, Taherabadi, Ghobadi, Mohammadi, & Jalali-Honarmand, 2013). Added to that, higher temperatures at that season may have increased cell respiration and carbohydrate waste in the Krebs cycle, decreasing net photosynthesis and root biomass (Taiz et al., 2017), which may have affected root depth.

Root depth varied across different sowing times, soil classes, and water condition treatments (Table 1), with a significant interaction between the three factors. During the first crop season, plants exhibited 30% deeper root penetration than during the second season. Mean root penetration depth reached 72.5 cm in the Ultisol and 57.3 cm in the Oxisol. Plants grown under water deficit showed deeper root penetration, although no significant difference was observed between the control in Ultisol and Oxisol during the first and second crop season, respectively. Rauf and Sadaqat (2007) also recorded deeper sunflower root penetration under water deficit conditions.

In contrast, plants grown under water excess exhibited less root penetration in both soils and sowing times. According to Grassini et al. (2007) and Yasumoto, Terakado, Matsuzaki, and Okada (2011), water excess limits sunflower root penetration, with horizontal growth prevailing close to the soil surface.

Root penetration was deeper in the Ultisol than in the Oxisol, which can be attributed to the fact that sandy soils, like the Ultisol, offer less resistance to root growth than clayey soils, like the Oxisol, especially under water deficit (Rosolem, Fernandez, Andreotti, & Crusciol, 1999). The sandy texture in the first 0.50 m depth of the Ultisol results in an early water deficit that may stimulate root growth (D'angria, Chiaranda, Magliulo, & Mori, 1995). Furthermore, sandy soils have more macropores, which are natural pathways for root growth (Torres & Saraiva, 1999). Under water deficit conditions, resistance to root penetration increases, therefore, plants grown in Ultisol show deeper root penetration than those grown in Oxisol. This result was also observed in maize, which exhibited lower resistance to root penetration in sandy soils (Rosolem et al., 1999), as well as in the same soil type with varying degrees of compaction (Stone & Silveira, 1999; Cardoso et al., 2006).

Our findings demonstrate that sunflower roots grow differently in the two soil types; however, roots depths were not as deep as those found in sandy soils, where roots can penetrate depths of 1.0 to 2.0 meters (Connor & Sadras, 1992; Rauf & Sadaqat, 2007). Therefore, sunflower roots can penetrate deep into the soil but are influenced by the type of soil. Such finding has a direct impact on the water holding capacity of a plant species for calculating soil water balance. Thus, the maximum depth of root penetration should be determined for each soil type and water condition to establish accurate water balance parameters.

Sunflower root distribution varied with soil water availability during crop development. Figures 2 and 3 depict the root length density (RLD) and accumulated root variable (ARV) in the Ultisol and Oxisol soils, respectively. Regardless of the water condition, most roots were found at a depth of 1.10 m, as this layer of soil is more fertile than deeper layers. A study by Sadras et al. (1989) found that 90% of sunflower roots were located at a depth of 0.20 m. Similarly, in soybean crops, most of the root number and mass, or root volume, are found in the surface layer at depths of 0.15 to 0.20 m (Torres & Saraiva, 1999; Cardoso et al., 2006).

In the Ultisol, the accumulated root variable had lower values at a depth of 0.10 m in the three development stages under water deficit conditions (Figure 2A, 2B, and 2C), indicating improved root distribution in deeper layers. Conversely, higher values were observed under water excess in the same soil layer, indicating a less favorable distribution in deeper layers (Figure 2G, H, and I). The control treatment exhibited an intermediate distribution, with significant root penetration and lateral distribution (Figure 2D, E, and F).

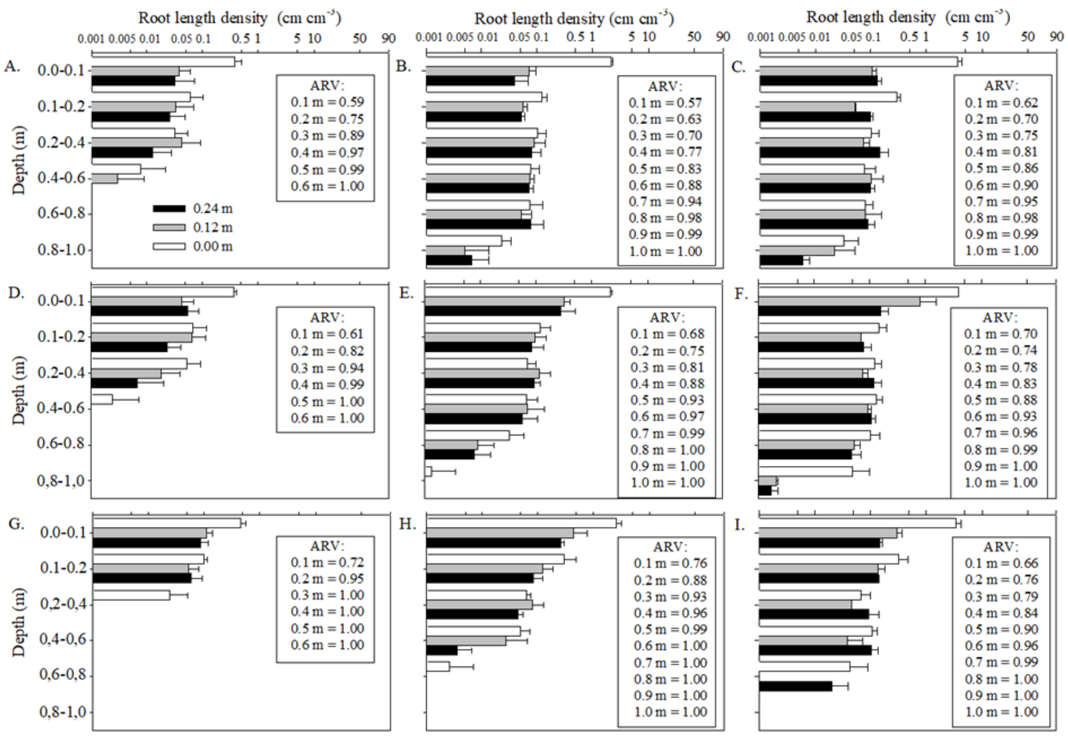

Figure 2. Horizontal and vertical distribution of sunflower roots under different water conditions at stages V10 (A, D, and G), R2 (B, E, and H), and R6 (C, F, and I). Horizontal distances evaluated in relation to plant position are 0.00, 0.12, and 0.24 m. Vertical distribution is shown through the accumulated root variable (ARV). The experiment was conducted in an Ultisol (Santa Maria/RS) and sown on September 6, 2013.

Root length density varied from 4.0 to 0.5 cm cm^{-3} from the 0.0-0.10 to 0.10-0.20 m depth layers, respectively. For Connor and Sadras (1992), it exponentially reduces as soil depth increases in sunflower crops. Our findings followed the trend found by Pivetta et al. (2011) for soybeans. Conversely, Caires et al. (2001b) found an average root length density of 1.7 cm cm^{-3} for soybeans in soil depths below 0.10 m. Similar values were recorded for barley, with means of 2.4 cm cm^{-3} in the first 0.10 m of depth, 0.57 cm cm^{-3} between 0.10 m and 0.20 m, 0.35 cm cm^{-3} between 0.20 m and 0.40 m, and 0.25 cm cm^{-3} between 0.40 m and 0.60 m (Caires et al., 2001a). We noted a significant increase in root length density in stages V10 (Figure 2A, D, and G), R2 (Figure 2B, E, and H), and R6 (Figure 2C, F, and I). Moreover, both root penetration and lateral distribution were maintained until stage R6 after anthesis, and at the beginning of grain filling.

The sunflower plants showed less root penetration in the Oxisol than in the Ultisol, especially under water deficit treatment (Figure 3G, H, and I). However, better lateral distribution in the first 0.10 m was observed under the control treatment in stage R6 (Figure 3F). Despite showing deeper root penetration (Figure 3A, B, and C), the plants subjected to water deficit exhibited a reduction in root length density down to 0.20 m compared to plants under the control treatment. As discussed earlier, soils with higher clay content restrict root penetration under water deficit conditions compared to moister soils (Rosolem et al., 1999; Kuster et al., 2013), which is why root growth and distribution were better in the control treatment.

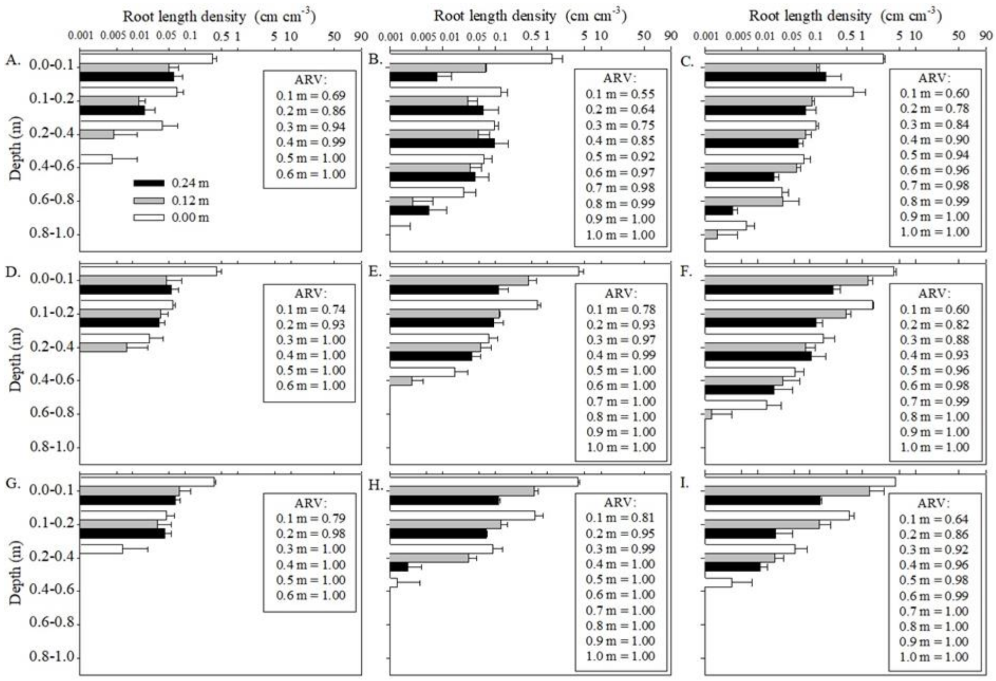

Figure 3. Horizontal and vertical distribution of sunflower roots under different water deficit (A, B, and C), control (D, E, and F), and water excess treatments (G, H, and I) at stages V10 (A, D, and G), R2 (B, E, and H), and R6 (C, F, and I). Horizontal distances evaluated in relation to plant position are 0.00, 0.12, and 0.24 m. Vertical distribution is shown through the accumulated root variable (ARV). The experiment was conducted in an Oxisol (Panambi/RS) and sown on September 7, 2013.

After analyzing the accumulated root variable (ARV) of the three treatments down to 0.10 m, the plants under water excess conditions had the highest values, followed by the control treatment. This indicates that under water excess, a larger percentage of roots concentrate in the surface soil layer, resulting in a predominant horizontal growth. However, water excess can reduce oxygen levels in the soil, which can limit sunflower root growth and even cause root senescence, depending on the intensity and duration of the water excess (Grassini et al., 2007; Yasumoto et al., 2011; Loose et al., 2017). This can result in reduced water availability due to the lower volume of soil exploited by the roots.

Table 2 shows the statistical analysis of root length density at different depths and distances from the plant. The control treatment had a higher root length density in the Ultisol in the layer from 0 to 0.10 m, which was significantly different from the water deficit and water excess treatments. In the Oxisol, the control and excess treatments did not differ in the same soil layer, while the lowest root length density occurred in the portions under water deficit. Regarding different depths, either in the Ultisol or in the Oxisol, root length density was higher in the soil layer from 0 to 0.10 m, which was significantly different from the remaining soil layers, except for the control treatment in the Oxisol, where the layer from 0.10 m to 0.20 m had a higher root length density than the deeper layers. The highest root length density in both soils occurred at 0.00 m from the plant position, which was significantly different from the remaining distances. In the Oxisol, the plants under water excess had a higher root length density at 0.12 m than at 0.24 m. At 0.00 m from the plant, root length density was lower in the Oxisol subjected to water deficit than in treatments with higher water availability.

Table 2. Root length density at different soil layers and distances from the sunflower plant (0.00, 0.12, and 0.24 m) at stage R6, for plants sown in the second crop season in an Ultisol (Santa Maria/RS) and an Oxisol (Panambi/RS).

	Root Length density (cm cm^{-3})								
	Depth (m)**						Distance (m)***		
	0 – 0.1	0.1 – 0.2	0.2 – 0.4	0.4 – 0.6	0.6 – 0.8	0.8 – 1.0	0.00	0.12	0.24
	Ultisol*								
DEF	1.28 b A	0.10 a B	0.11 a B	0.09 a B	0.04 a B	0.02 a B	0.45 a A	0.07 a B	0.10 a B
CONT	1.65 a A	0.15 a B	0.11 a B	0.11 a B	0.07 a B	0.02 a B	0.52 a A	0.15 a B	0.09 a B
EXC	1.31 b A	0.20 a B	0.08 a B	0.12 a B	0.08 a B	0.00 a B	0.57 a A	0.13 a B	0.09 a B
	Oxisol								
DEF	0.93 b A	0.29 b B	0.09 a B	0.05 a B	0.02 a B	0.00 a B	0.38 b A	0.07 b B	0.06 a B
CONT	1.81 a A	0.73 a B	0.12 a C	0.03 a C	0.01 a C	0.00 a C	0.79 a A	0.29 ab B	0.12 a B
EXC	1.84 a A	0.24 b B	0.03 a B	0.00 a B	0.00 a B	0.00 a B	0.67 a A	0.38 a B	0.05 a C
CV (%)	36.15								

*Means followed by the same letter in the row (uppercase letter) and in the column (lowercase letter) did not differ from each other by Tukey's test ($p < 0.05$). Sowing dates: September 6, 2013, in Santa Maria/RS; September 7, 2013, in Panambi/RS. Treatments: control (soil moisture between 75 and 100% WHC); water excess (soil moisture between 90% WHC and the determined saturation point); water deficit (soil moisture between 40 and 60% WHC). **Mean distance values. ***Mean depth values.

Figure 4 shows the root growth and distribution in both soils during the second crop season. The Ultisol soil subjected to water deficit treatment (Figure 4A) resulted in aggressive primary root penetration and better root distribution in the soil profile. However, the control and water excess treatments also led to the deepening of the root system, but there was a higher root volume in the initial layer, close to the surface (Figure 4B and C). It should be noted that the treatments were applied from stage V6 onwards, indicating that the levels of water excess or deficit were strong enough to change the balance between the plant hormones and cause different root growth in each environmental condition. Plants subjected to water deficit treatment may have had higher root concentrations of cytokinins and ABA, playing a role in root penetration (Aloni et al., 2006; Xiong et al., 2006), while plants subjected to water excess may have had higher concentrations of ethylene gas and auxins, which could cause the senescence of secondary root production close to the soil surface (Acharya & Assmann, 2009).

The moisture difference in the soils subjected to the water condition treatments caused a change in the root growth pattern (Figure 4). Under the control and water excess conditions, primary roots did not penetrate as much as under water deficit. Moreover, there was no difference between the control and the water excess treatments. This may be because the Ultisol has a higher sand percentage in the layers above the B textural horizon, allowing faster water infiltration and drainage than soils with higher clay contents in the initial layers (Alves, Suzuki, & Suzuki, 2007). Therefore, water excess is drained faster, causing fewer adverse effects, and allowing even the roots subjected to this treatment to grow into deeper layers.

Under water deficit, primary roots penetrated less aggressively in the Oxisol than did in the Ultisol (Figure 4B). The difference between Figures 4A and B indicates that sunflower roots in the Oxisol under water deficit are less deep and show lower dry mass growth than in the Ultisol. The root growth pattern in the Oxisol highlights the difficulty of primary roots in penetrating the soil due to higher physical resistance. Rosolem et al. (1999) suggested that penetration resistance increases as the soil dries, especially in soils with clay contents higher than 40%, such as Oxisols. Nonetheless, some plants in the Oxisol showed considerable deepening of the root system under water deficit conditions, reaching up to 0.70 m in the second crop season (Figure 4B). In the control treatment, root distribution and formation were favorable in both horizontal and vertical directions, occupying a larger soil volume (Figure 4D). Under water excess conditions, roots were concentrated in the first 0.20 m, forming more superficial roots (Figure 4F). Compared to the Ultisol, the Oxisol has less efficient drainage and requires a longer time to return to field capacity after saturation (Alves et al., 2007). This is an important factor to consider regarding the sunflower root growth pattern under this condition, especially during El Niño years when rainfall is more abundant in the two locations where data were collected (Grimm, Barros, & Doyle, 2000).

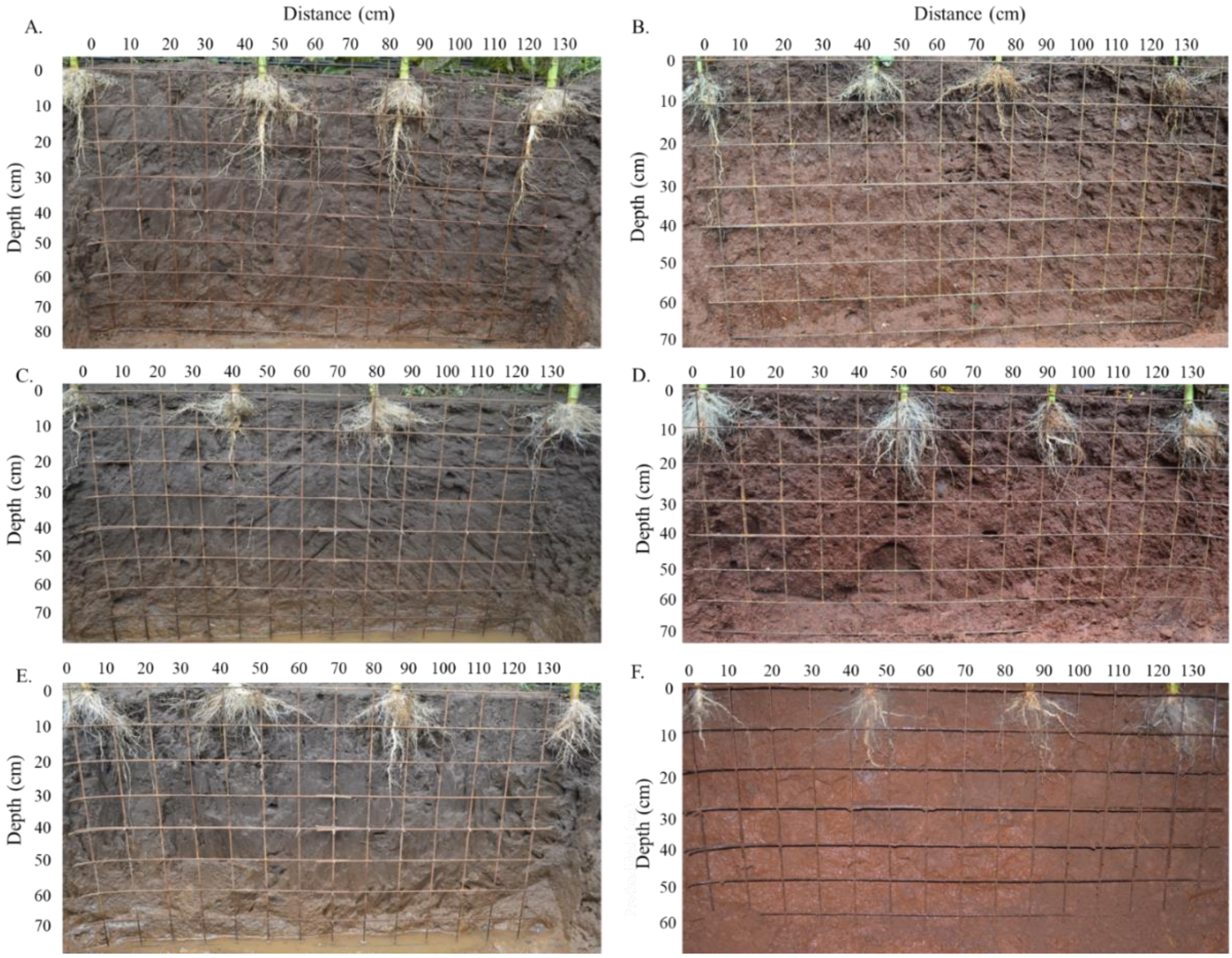

Figure 4. Root distribution of sunflower plants at stage R6 under water deficit (A and B), control (C and D), and water excess conditions (E and F) in an Ultisol (A, C, and E) (Santa Maria/RS) and in an Oxisol (B, D, and F) (Panambi/RS) during the second crop season.

Conclusion

Regardless of the soil water condition, sunflower root penetration is deeper in the Ultisol than in the Oxisol. Water deficit stimulates deeper root penetration in sunflower, while water excess promotes surface root growth. Soil water content between 75 and 100% of the water holding capacity (WHC) provides a balanced distribution of sunflower root system and enhances root growth in terms of dry matter mass. Sunflower plants sown at the beginning of September (first crop season) exhibit deeper root penetration and greater root dry matter mass compared to those sown at the beginning of January (second crop season).

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References

Acharya, B. R., & Assmann, S. M. (2009). Hormone interactions in stomatal function. *Plant Molecular Biology*, *69*(4), 451-462. DOI: https://doi.org/10.1007/s11103-008-9427-0

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements*. Rome, IT: FAO. (FAO Irrigation and drainage paper, 56)

Aloni, R., Aloni, E., Langhans, M., & Ullrich, C. I. (2006). Role of cytokinin and auxin in shaping root architecture: regulating vascular differentiation, lateral root initiation, root apical dominance and root gravitropism. *Annals of Botany*, *97*(5), 883-893. DOI: https://doi.org/10.1093/aob/mcl027

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, *22*(6), 711-728. DOI: https://doi.org/10.1127/0941-2948/2013/0507

Alves, M. C., Suzuki, L. G. A. S., & Suzuki, L. E. A. S. (2007). Densidade do solo e infiltração de água como indicadores da qualidade física de um Latossolo Vermelho distrófico em recuperação. *Revista Brasileira de Ciência do Solo*, *31*(4), 617-625. DOI: http://dx.doi.org/10.1590/S0100-06832007000400002

Asseng, S., Ritchie, J. T., Smucker, A. J. M., & Robertson, M. J. (1998). Root growth and water uptake during water deficit and recovering in wheat. *Plant and Soil*, *201*(2), 265-273. DOI: https://doi.org/10.1023/A:1004317523264

Bergonci, J. I., Bergamaschi, H., Santos, A. O., França, S., & Radin, B. (2001). Eficiência da irrigação em rendimento de grãos e matéria seca de milho. *Pesquisa Agropecuária Brasileira*, *36*(7), 949-956. DOI: http://dx.doi.org/10.1590/S0100-204X2001000700004

Böhm, W. (1979). *Methods of studying root systems*. Berlin, GE: Springer.

Brand, S. I., Heldwein, A. B., Radons, S. Z., Maldaner, I. C., Hinnah, F. D., Guse, F. I., & Silva, J. R. (2020). Effect of *Alternaria* and *Septoria* spot on sunflower yield. *International Journal of Biometeorology*, *64*(12), 2153-2160. DOI: https://doi.org/10.1007/s00484-020-02006-8

Caires, E. F., Feldhaus, I. C., & Blum, J. (2001a). Crescimento radicular e nutrição da cevada em função da calagem e aplicação de gesso. *Bragantia*, *60*(3), 213-223. DOI: https://doi.org/10.1590/S0006-87052001000300009

Caires, E. F., Fonseca, A. F., Feldhaus, I. C., & Blum, J. (2001b). Crescimento radicular e nutrição da soja cultivada no sistema plantio direto em resposta ao calcário e gesso na superfície. *Revista Brasileira de Ciência do Solo*, *25*(4), 1029-1040. DOI: https://doi.org/10.1590/S0100-06832001000400025

Cardoso, E. G., Zotarelli, L., Piccinin, J. L., Torres, E., Saraiva, O. F., & Guimarães, M. D. F. (2006). Sistema radicular da soja em função da compactação do solo no sistema de plantio direto. *Pesquisa Agropecuária Brasileira, 41*(3), 493-501. DOI: https://doi.org/10.1590/S0100-204X2006000300017

Companhia Nacional de Abastecimento [CONAB]. (2022). *Série histórica das safras: Girassol*. Retrieved on Aug. 15, 2022 from https://www.conab.gov.br/info-agro/safras/serie-historica-das-safras

Connor, D. J., & Sadras, V. O. (1992). Physiology of yield expression in sunflower. *Field Crops Research*, *30*(3), 333-389. DOI: https://doi.org/10.1016/0378-4290(92)90006-U

D'Andria, R., Chiaranda, F. Q., Magliulo, V., & Mori, M. (1995). Yield and soil water uptake of sunflower sown in spring and summer. *Agronomy Journal*, *87*(6), 1122-1128. DOI: https://doi.org/10.2134/agronj1995.00021962008700060014x

Dourado-Neto, D., García y García, A., Fancelli, A. L., Frizzone, J. A., & Reichardt, K. (1999). Balance hídrico ciclico y secuencial: estimación de almacenamiento de agua en el suelo. *Scientia Agricola*, *56*(3), 537-546. DOI: https://doi.org/10.1590/S0103-90161999000300005

Ghobadi, M., Taherabadi, S., Ghobadi, M. E., Mohammadi, G. R., & Jalali-Honarmand, S. (2013). Antioxidant capacity, photosynthetic characteristics and water relations of sunflower (*Helianthus annuus* L.) cultivars in response to drought stress. *Industrial Crops and Products*, *50*, 29-38. DOI: https://doi.org/10.1016/j.indcrop.2013.07.009

Grassini, P., Indaco, G. V., Pereira, M. L., Hall, A. J., & Trápani, N. (2007). Responses to short-term waterlogging during grain filling in sunflower. *Field Crops Research*, *101*(3), 352-363. DOI: https://doi.org/10.1016/j.fcr.2006.12.009

Grimm, A. M., Barros, V. R., & Doyle, M. E. (2000). Climate variability in southern South America associated with El Niño and La Niña events. *Journal of Climate*, *13*(1), 35-58. DOI: https://doi.org/10.1175/1520-0442(2000)013<0035:CVISSA>2.0.CO;2

Kage, H., Kochler, M., & Stützel, H. (2004). Root growth and dry matter partitioning of cauliflower under drought stress conditions: measurement and simulation. *European Journal of Agronomy*, *20*(4), 379-394. DOI: https://doi.org/10.1016/S1161-0301(03)00061-3

Kuster, T. M., Arend, M., Günthardt-Goerg, M. S., & Schulin, R. (2013). Root growth of different oak provenances in two soils under drought stress and air warming conditions. *Plant and Soil*, *369*(1-2), 61-71. DOI: https://doi.org/10.1007/s11104-012-1541-8

Loose, L. H., Heldwein, A. B, Silva, J. R., & Bortoluzzi, M. P. (2019). Yield and quality of sunflower oil in Ultisol and Oxisol under water regimes. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *23*(7), 532-537. http://dx.doi.org/10.1590/1807-1929/agriambi.v23n7p532-537

Maldaner, I. C., Heldwein, A. B, Bortoluzzi, M. P., Righi, E. Z., Lucas, D. D. P., Loose, L. H., & Hinnah, F. D. (2018). Base temperature and thermal time of developmental subperiods in sunflower. *Brazilian Journal of Agriculture*, *93*(3), 234-249. DOI: https://doi.org/10.37856/bja.v93i3.3173

Masalia, R. R., Temme, A. A., Torralba, N. D. L., & Burke, J. M. (2018). Multiple genomic regions influence root morphology and seedling growth in cultivated sunflower (*Helianthus annuus* L.) under well-watered and water-limited conditions. *PLoS ONE*, *13*(9), 1-23. DOI: https://doi.org/10.1371/journal.pone.0204279

Ni, X. L., Gui, M. Y., Tan, L. L., Zhu, Q., Liu, W. Z., & Li, C. X. (2019). Programmed cell death and aerenchyma formation in water-logged sunflower stems and its promotion by ethylene and ROS. *Frontiers in Plant Science*, *9*(1928), 1-16. DOI: https://doi.org/10.3389/fpls.2018.01928

Paul, P. L. C., Bell, R. W., Barrett-Lennard, E. G., Kabir, E., Mainuddin, M., & Sarker, K. K. (2021). Short-Term waterlogging depresses early growth of sunflower *(Helianthus annuus* L.) on saline soils with a shallow water table in the coastal zone of bangladesh. *Soil Systems*, *5*(68), 1-12. DOI: https://doi.org/10.3390/soilsystems5040068

Pereira, A. R. (2005). Simplificando o balanço hídrico de Thornthwaite-Mather. *Bragantia*, *64*(2), 311-313. DOI: http://dx.doi.org/10.1590/S0006-87052005000200019

Pivetta, L. A., Castoldi, G., Santos, G. P., & Rosolem, C. A. (2011). Crescimento e atividade de raízes de soja em função do sistema de produção. *Pesquisa Agropecuária Brasileira*, *46*(11), 1547-1554. DOI: http://dx.doi.org/10.1590/S0100-204X2011001100017

Rauf, S., & Sadaqat, H. A. (2007). Effects of varied water regimes on root length, dry matter partitioning and endogenous plant growth regulators in sunflower (*Helianthus annuus* L.). *Journal of Plant Interactions*, *2*(1), 41-51. DOI: https://doi.org/10.1080/17429140701422512

Righi, E. Z., Heldwein, A. B., Maldaner, I. C., Lucas, D. D. P., & Stüker, P. E. (2015). Balance of longwave radiation employing the rate of solar radiation for Santa Maria, Rio Grande do Sul, Brazil. *Revista Ciência Agronômica*, *46*(1), 29-37. DOI: https://doi.org/10.1590/S1806-66902015000100004

Rosolem, C. A., Fernandez, E. M., Andreotti, M., & Crusciol, C. A. C. (1999). Crescimento radicular de plântulas de milho afetado pela resistência do solo à penetração. *Pesquisa Agropecuária Brasileira*, *34*(5), 821-828. DOI: http://dx.doi.org/10.1590/S0100-204X1999000500013

Sadras, V. O., Hall, A. J., Trapani, N., & Vilella, F. (1989). Dynamics of rooting and root-length: leaf-area relationships as affected by plant population in sunflower crops. *Field Crops Research*, *22*(1), 45-57. DOI: https://doi.org/10.1016/0378-4290(89)90088-9

Schneiter, A. A., & Miller, J. F. (1981). Description of sunflower growth stages. *Crop Science*, *21*(6), 901-903. DOI: https://doi.org/10.2135/cropsci1981.0011183X002100060024x

Sentelhas, P. C., Nogueira, S. D. S. S., Pedro Júnior, M. J., & Santos, R. R. (1994). Temperatura-base e graus-dia para cultivares de girassol. *Revista Brasileira de Agrometeorologia*, *2*(1), 43-49.

Sharp, R. E., Poroyko, V., Hejlek, L. G., Spollen, W. G., Springer, G. K., Bohnert, H. J., & Nguyen, H. T. (2004). Root growth maintenance during water deficits: physiology to functional genomics. *Journal of Experimental Botany*, *55*(407), 2343-2351. DOI: https://doi.org/10.1093/jxb/erh276

Soares, M. M, Freitas, C. D. M., Oliveira, F. S., Mesquita, H. C., Silva, T. S., & Silva, D. V. (2019). Effects of competition and water deficiency on sunflower and weed growth. *Revista Caatinga*, *32*(2), 318-328. DOI: https://doi.org/10.1590/1983-21252019v32n204rc

Stone, L. F., & Silveira, P. M. (1999). Efeitos do sistema de preparo na compactação do solo, disponibilidade hídrica e comportamento do feijoeiro. *Pesquisa Agropecuária Brasileira*, *34*(1), 83-91. DOI: https://doi.org/10.1590/S0100-204X1999000100012

Taiz, L., Zeiger, E., Møller, I. M., & Murph, A. (2017). *Fisiologia vegetal*. Porto Alegre, RS: Artmed.

Torres, E., & Saraiva, O. F. (1999). *Camadas de impedimento mecânico do solo em sistemas agrícolas com a soja*. Londrina, PR: Embrapa.

Xiong, L., Wang, R. G., Mao, G., & Koczan, J. M. (2006). Identification of drought tolerance determinants by genetic analysis of root response to drought stress and abscisic acid. *Plant Physiology*, *142*(3), 1065-1074. DOI: https://doi.org/10.1104/pp.106.084632

Yasumoto, S., Terakado, Y., Matsuzaki, M., & Okada, K. (2011). Effects of high water table and short-term flooding on growth, yield, and seed quality of sunflower. *Plant Production Science*, *14*(3), 233-248. DOI: https://doi.org/10.1626/pps.14.233