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CROP PRODUCTION

Modification of canola cultivation conditions in a waterlogging-susceptible subtropical environment

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ABSTRACT. Waterlogging directly interferes with the production capacity of agricultural crops in response to the morphophysiological changes caused to plants. Since the cultivation of poorly drained soils is traditionally avoided, this study aimed to evaluate the possibility of expanding canola cultivation into waterlogged soils using soil surface drainage and different row spacings in lowland areas of Rio Grande do Sul, Brazil. Treatments consisted of the presence and absence of surface drains at 0.25 m depth and row spacings of 0.17, 0.34, 0.51, and 0.68 m arranged in two-factorial randomized blocks with four replications, in 2018 and 2019. In this study, growth traits, yield components, and the final grain yield of canola were evaluated. The increase in lateral branching in canola plants was found to be directly related to waterlogging and negatively affected yield. The use of drains positively impacted the number of pods per plant, seeds per pod, the 1,000 seeds weight, and grain yield. The more intense waterlogging conditions in 2018 resulted in the highest grain yield and superior production traits were obtained with row spacings between 0.41 and 0.48 m. In the absence of waterlogging, the 0.17 m row spacing was more productive. Canola cultivation can occur in waterlogged soils in the presence of surface drainage and at row spacings ranging from 0.40 to 0.50 m.

Keywords: drainage; row spacing; water table; lowlands; grain yield.

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Introduction

Canola (*Brassica napus* L.) is an oilseed crop with high nutritional value and multiple grain uses (Gularte, Macedo, & Panozzo, 2020). Its annual cultivation occurs in areas predominantly close to the oilseed industry and well-drained highland soils. In this scenario, idle autumn/winter areas used for rice and, more recently, soybean cultivation could be incorporated with this *Brassica* species, resulting in economic returns to producers by breaking the pest and disease cycle, allowing better weed control, and optimizing the use of infrastructure in rural properties (Fontoura Júnior et al., 2020).

These lowland soils are limited by the natural drainage process because coupled with the relief that is unfavorable to surface runoff, the low atmospheric demand for water vapor, and the more abundant autumn/winter rainfall, cause waterlogging to become more frequent and prolonged (Bortoluzzi, Heldwein, Trentin, Maldaner, & Silva, 2020; Goulart, Reichert, & Rodrigues, 2020). Soil waterlogging compromises gas exchange in the root system, primarily oxygen and CO_2 (Ploschuk, Miralles, Colmer, Ploschuk, & Striker, 2020). In the absence of morphoanatomical changes in non-adapted plants, the compromised gas flow in the soil may result in reduced photosynthetic levels, nutrient uptake, leaf senescence, and growth reduction (Zhu, 2016; Liu, Tan, Sol, & Zwiazek, 2020; Ploschuk et al., 2020).

Canola is considered susceptible to cultivation in waterlogged soils (Xu et al., 2015; Tartaglia et al., 2018; Ploschuk et al., 2020). However, its cultivation in these environments is possible using more tolerant cultivars (Zaman, Malik, Erskine, & Kaur, 2019; Guo et al., 2020), adequate soil (Pashakolaee, Shahnazari, & Talukolaee, 2017), and appropriate crop management (Habibzadeh, Sorooshzadeh, Pirdashti, & Modarres-Sanavy, 2013). From this perspective, the spatial distribution of plants and soil surface drainage are two management practices that influence crop growth, development, and yield.

Changes in the spacing between rows and/or between plants interfere directly with the interspecific and intraspecific competition for essential elements such as solar radiation, water, nutrients, and physical space (Krüger et al., 2011a; Peruzatto et al., 2017). Several studies have been conducted with spatial changes in the canopy stand (Krüger et al., 2011a; Bandeira, Chavarria, & Tomm, 2013; Kuai et al., 2015). However, there is lack of information about the adverse effects of waterlogging on canola behavior, development, and production capacity.

Surface drainage in lowlands, commonly used for soybean and maize in spring and summer (Emygdio, Rosa, & Oliveira, 2017; Melo et al., 2021), could be an alternative for canola cultivation in soils with poor drainage and water table rise during intermittent periods of autumn and winter. Allied to this, changes in the spatial arrangement of plants could create micrometeorological conditions more favorable to canola growth and development, thereby reducing losses associated with excess soil and air moisture.

If waterlogging-sensitive species can be cultivated in spring and summer, such as soybean with soil surface drainage, it might also be valid during autumn and winter. This practice could reduce the idleness of lowlands during these seasons and allow the use of surface drainage structure for spring and summer crops with direct seeding. However, under the subtropical conditions of Brazil, there is still little information in the literature about the effect of soil waterlogging on the canola crop and how changes in plant arrangement in these environments could impact the production capacity of this crop. Therefore, this study aimed to evaluate the possibility of expanding canola cultivation into waterlogged soils using surface drainage and different row spacings in lowland areas of Rio Grande do Sul State, Brazil.

Material and methods

The present study was conducted in the Central Depression region of Rio Grande do Sul, Brazil, in a lowland area at the Plant Science Department of the Federal University of Santa Maria (29°43'23" S; 53°43'15" W; 95 m) in 2018 and 2019. The region has a Cfa humid subtropical climate according to Köppen classification, with a normal mean temperature of 22.0°C in the hottest month (January) and 12.9°C in the coldest month (June) (Heldwein, Buriol, & Streck, 2009). Rainfall is distributed regularly across all months of the year, with an annual mean of 1,712.4 mm in 92 years and a high probability of significant and frequent waterlogging between May and September associated with low evaporative demand (Buriol, Estefanel, Swarowsky, & D'avila, 2006).

The experimental design consisted of randomized blocks in strips and split plots with four replications and a 2 x 4 factorial scheme. The strips received the levels of the soil surface drainage factor (presence (PSD) and absence (ASD) of surface drains), while the split plots received different spacings between planting rows (0.17, 0.34, 0.51, and 0.68 m), with four replications for each treatment and a sufficient planting density to ensure the establishment of 40 plants per m^2 in all treatments after thinning was realized at the V1 development stage, according to the phenological scale adapted from CETIOM (Iriarte & Valetti, 2008). The experimental units encompassed an area of 100 m^2 (10 x 10 m) and a useful area of 72.25 m^2 (8.5 x 8.5 m). The surface drains were opened using appropriate machinery to obtain a groove 0.25 m deep and 0.25 m wide around the experimental units. The surface drains were carried out with the aid of a rotary trencher with groove dimensions of 0.25 m deep and 0.25 m wide, around the experimental units. This traction equipment was used because of its great commercial availability and employability in lowland areas for surface drainage of the crop soil.

The canola cultivar Diamond was chosen for cultivation due to its early cycle, high grain oil content, polygenic disease resistance, and wide use in the farming areas of Rio Grande do Sul. The crop was established by conventional cultivation, predominant in lowland areas, in addition to seed deposition at a maximum depth of 0.02 m. The rows were north-south oriented. In both crop years, sowing was performed on dates close to early June (May 29, 2018 and June 6, 2019).

Soil correction, basal fertilization, and topdressing fertilization were performed after soil analysis using soil samples collected before each crop year and calculated to an estimated 3 Mg ha^{-1}, according to the guidelines of the Manual for Canola Fertilization in RS and SC (SBCS, 2016). Topdressing fertilization consisted of amide and ammoniacal nitrogen supplied as urea and ammonium sulfate, both applied at half dose during the rosette stage (V4) and at the commencement of plant flowering (IF). Ammonium sulfate was used to supplement sulfur. The other crop management and phytosanitary practices were performed according to their need and following specific technical guidelines (Tomm, Wiethölter, Dalmago, & Santos, 2009).

The meteorological variables were monitored with an automatic weather station belonging to the 8th Meteorology District of INMET, located at the UFSM campus within a 200 m radius from the site of the experiment. Groundwater monitoring was achieved by taking readings in observation wells (piezometers) arranged to a depth of 0.30 m at the center of each experimental unit.

The evaluations consisted of determining the growth and yield traits of the canola crop. Plant height (PH) was established as the distance from the base of the plant to the tip of the main stem and was measured randomly in ten plants within the useful area of each experimental unit when plants reached physiological maturation. The same opportunity was used to count the plants contained within a randomly delimited 2.7 m^2 area from each experimental unit to adjust the final plant density (PD) of each treatment.

The number of branches per plant (NB) was determined by randomly collecting six plants per plot and counting the branches that emerged from the main stem. The number of pods per plant (NPP), the number of seeds per pod (NSP), and the 1,000 seeds weight (TSW) were determined using the same six plants. The NPP was obtained by counting all fertile and infertile pods on the branches and calculating their mean value per plant. The NSP was determined by sectioning 20 random pods and counting all viable grains. Finally, the TSW was determined by threshing the seeds from the collected plants, and during seeds homogenization, three subsamples of 100 seeds were counted for the subsequent determination of the one thousand seeds weight.

Grain yield was evaluated when the plants reached physiological maturity, with 50% of the grains showing a brown color. All plants from a 4.08 m^2 area at the center of the experimental units were collected. This harvested area comprised 12, 6, 4, and 3 rows measuring two linear meters for plant spacings of 0.17, 0.34, 0.51, and 0.68 m, respectively.

Harvest was performed by cutting the plants close to the soil and storing them in nonwoven fabric bags, which were then transferred for natural drying, to a dry and ventilated environment. After mass stabilization, the samples were threshed manually, and the grains were separated from the rest of the shoot fresh matter and oven-dried at 60°C until gaining moisture uniformity. After weighing, the yield was corrected to the standard moisture of 8%.

Data were tested for normality of errors and homogeneity of variances of the treatments. In the analysis of variance, the quantitative data were subjected to regression analysis when significant by the F-test. In contrast, the means of the qualitative data were compared by the Scott-Knott test at 5% probability using the statistical program SISVAR (Ferreira, 2014).

Results and discussion

The cumulative rainfall values during canola growth and development (May-October) were 643 and 591 mm in 2018 and 2019, respectively (Figure 1a and c). However, in soils with surface drainage problems and susceptible to groundwater elevation, large excess rainfall can become an obstacle to the success of rapeseed cultivation. Thus, the greatest intensity and persistence of soil waterlogging in 2018 was observed in the vegetative phase of the crop, especially at the end of the rosette and stem elongation sub-period of the plants, with a limitation of the aerated soil layer restricted to a maximum of 0.05 m for more than 30 days in ASD (Figure 1a). During the crop development cycle for ASD and PSD, 27 and 14 measurements were observed respectively (interleaved every two days) with elevation of the water table to the soil surface; however, in PSD there was no persistence in the soil water table level.

In 2019, only four events were observed with a short duration of soil water table rise with greater intensity in ASD, covering both the vegetative and reproductive phases of the canola crop (Figure 1c). With the presence of drains (PSD), although there was excess rain during the development of the crop in 2019, an aerated layer of at least 0.12 m was observed in the soil for the highest intensity of soil water table elevation. This indicates that the drainage system was efficient. In this sense, the lower elevation of the water table provided an aerated zone suitable for root system growth, with the supply of nutrients and water to meet its vegetative and reproductive growth (Zou et al., 2014).

The average availability of global solar radiation during the crop cycle, between Jun. 1st and Oct. 15th of each year, was on average 10.71 and 12.30 MJ m^{-2} day^{-1} and 1,467.27 and 1,685.10 MJ m^{-2} in the accumulated, respectively, for 2018 (Figure 1b) and 2019 (Figure 1d). In the initial development stage (seedling, SS) lower availability of solar radiation was observed with daily averages of 7.63 and 8.82 MJ m^{-2} day^{-1} in 2018 and 2019, respectively. The biggest difference between years of cultivation was found in the second half of September, where there was 54.3% greater availability of solar radiation in 2019 than in 2018, which coincided with the sub-period between the end of flowering and grain filling.

The air temperature ranged between 5.1 and 26.4°C in 2018, and 4.5 and 31.9°C in 2019, respectively, for TAmin and TAmax (Figure 1b and d). Air temperature averages were observed for the subperiod between emergence and end of rosette of 13.3 and 15.3°C and end of rosette until beginning of flowering with 11.2 and 14.6°C for 2018 and 2019, respectively. According to Morrison, Mcvetty, and Shaykewich (1989), the growth of canola is favored in the vegetative phase with temperatures between 13.0 and 22.0°C, with an average temperature around 18.0°C. In the reproductive period, high temperatures occurred with greater predominance, and in 2019 a higher temperature rise was observed in the daytime period, reaching the maximum air temperature of 34.1°C. Robertson, Jeffrey, Unterschultz, and Boxall (2013) reported that the exposure of canola crops during the flowering period to temperatures above TB (29°C) caused a 0.08% reduction in canola grain yield for each hour of exposure.

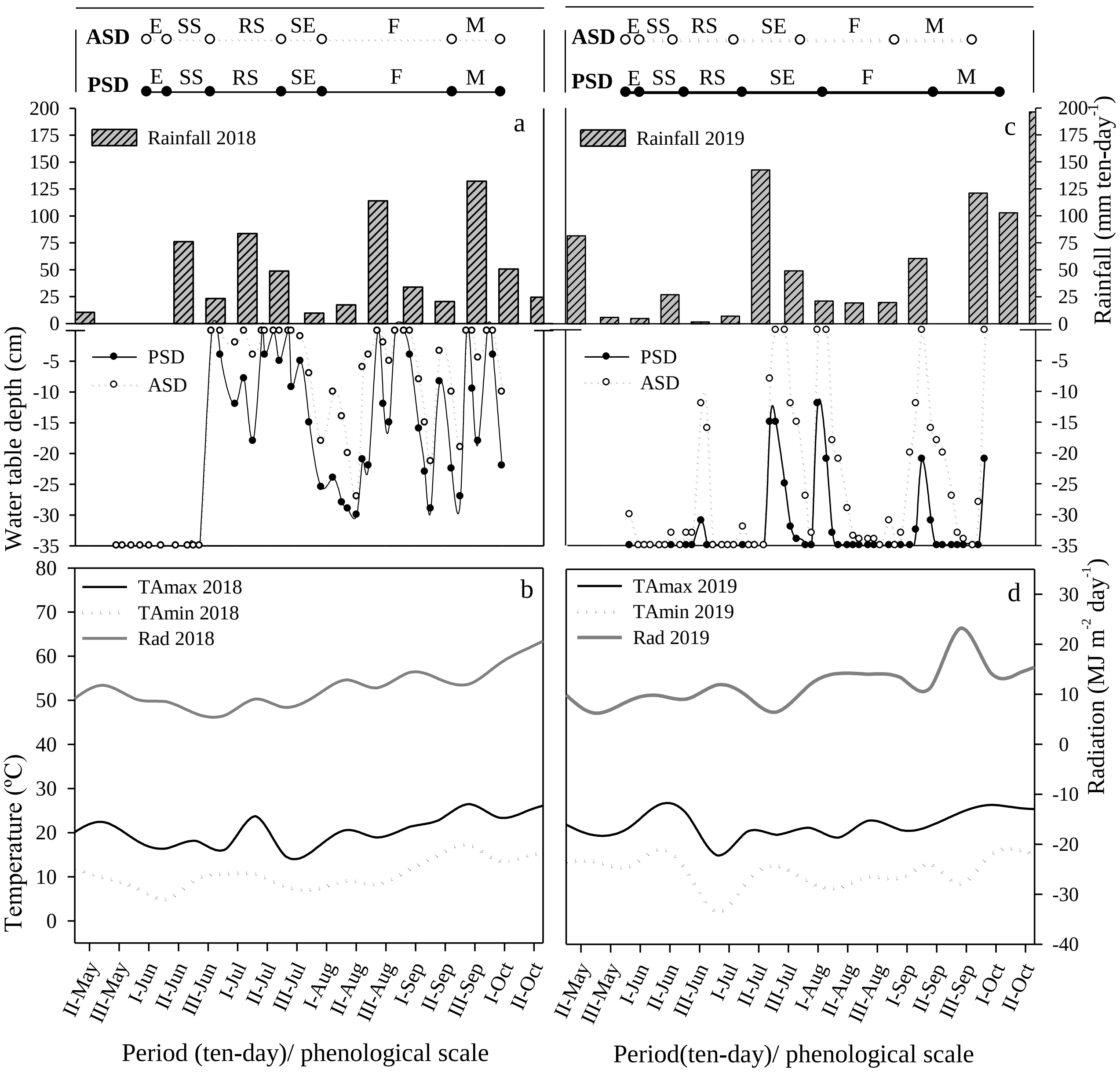

Figure 1. Rainfall (a, c), global solar radiation (b, d), daily maximum (TAmax) and minimum (TAmin) air temperature (b, d), and water table depth (WTD, a, c)) in a system presence surface drainage (PSD) and absence drains (ASD) in each cultivation month in 2018 (a, b) and 2019 (c, d). Phenological subperiod of emergency (E), seedling (SS), Rosette (RS), stem elongation (SE), flowering (F), and maturation (M) according to the phenological scale of Iriarte and Valetti (2008).

Plant height is affected by soil waterlogging during cultivation. In the absence of drainage, canola reached plant heights of 0.82 m and 0.92 m in 2018 (Figure 2a) and 2019, respectively (Figure 2b). When using surface drains (PSD), plant height increased by 22% and 43% in the respective years.

In the comparison for waterlogging, the highest elevation of the soil water table, observed in 2018 (Figure 2a), contributed the most significant decrease to canola plant height, especially in treatments submitted to ASD. The decrease in the aerated soil layer caused by water table rise modulates biochemical and physiological changes in plants, directly impacting plant morphology (Liu et al., 2020; Ploschuk et al., 2020). The decrease in leaf area index (LAI) due to leaf senescence in response to ethylene accumulation (Santos et al., 2020) reduced the synthesis of photoassimilates and resulted in the availability of more energy for growth.

Studies developed in the field by Zhou et al. (2014) and Santos et al. (2020) under waterlogging conditions, highlighted reductions in plant height of 50 and 57%, respectively. In a controlled environment, Rossi et al. (2015) found similar results as the growth of canola plants was affected in aerated soil layers no deeper than 0.20 m, whereas restrictions at 0.10 m significantly compromised plant height. In this scenario, the use of 0.25 m grooves may have provided a sufficient soil layer for canola to perform its gas exchange and nutrient uptake processes.

With regard to the final plant density, a negative linear response was observed with the increase in row spacing in the two years and the two drainage levels. In 2018, modification in the spatial arrangement of plants from 0.17 to 0.68 m resulted in a plant density reduction of 40.8 and 43.7% in the PSD and ASD treatments, respectively (Figure 2c). In 2019, the same plant arrangement modification reduced the initial plant stand of 40 plants m^{-2} to 29.2 and 31.9 plants per m^{-2} for the PSD and ASD treatments, respectively (Figure 2d). From this perspective, the increase in intraspecific competition for photosynthetically active radiation (PAR), nutrients, and physical space with the increased plant density in the row is the probable cause of reduction in the final plant density (Krüger et al., 2011a).

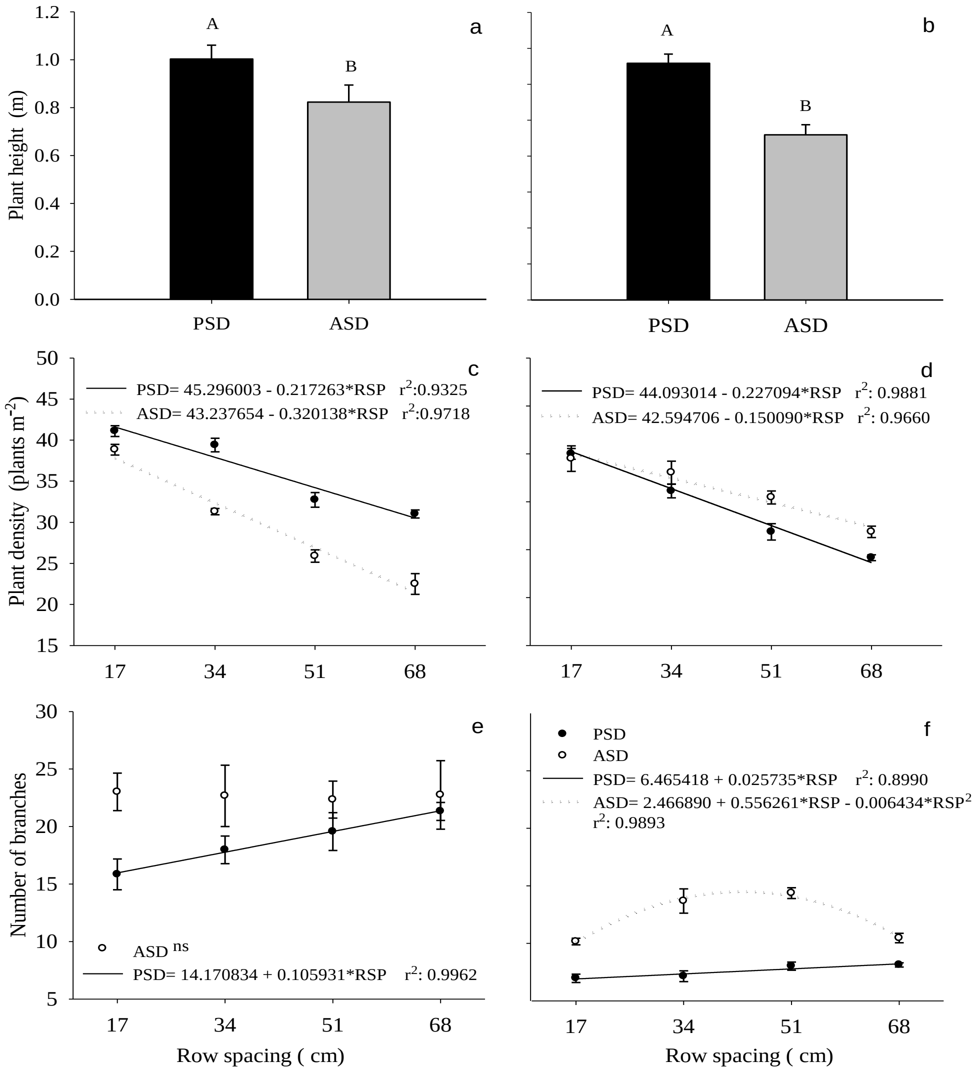

Figure 2. Plant height (a, b), final plant density (c, d), and number of branches per plant (e, f) of canola plants grown in the presence (PSD) and absence of soil surface drainage (ASD) at four different row spacings (RSP) in 2018 (a, c, e) and 2019 (b, d, f).

In 2018, the use of drains (PSD) allowed the persistence of plant density 5.5, 20.6, 20.9, and 27.5% higher than the ASD in the respective spacings of 0.17, 0.34, 0.51, and 0.68 m (Figure 2c). In 2019, the higher availability of solar radiation associated with fewer rainfall events and effective drainage in environments with drains (Figure 1c) allowed a higher growth of canola plants, resulting in more intense intraspecific competition in the plant row and greater plant density reduction in these environments compared to the ASD treatment. According to Zou et al. (2014), the decrease in plant stand is associated with the limitation of physical space and natural resources in very close plant canopies, thus increasing the occurrence of dominated (suppressed) plants.

Similar results were obtained by Kuai et al. (2015), with lower plant mortality when using a 0.15 m spacing between rows and 45 plants m^{-2}. However, the increase in row spacing intensified the reduction in the final density. Zou et al. (2014) tested different genotypes under waterlogging conditions and observed that more than 50% showed a significant reduction in plant density, with reductions greater than half the initial canopy.

The total number of branches (NTR) increased as the spacing between sowing rows increased in PSD in both 2018 (Figure 2e) and 2019 (Figure 2f). These results corroborate Bagheri, Sharghi, and Yazdani (2011) and Krüger, Silva, Medeiros, Dalmago, and Gaviraghi (2011b), who observed that the increase in row spacing from 0.15 to 0.45 m and from 0.20 to 0.60 m increased the number of branches by 24.4 and 43.0%, respectively. The higher number of lateral branches in wider spacings is associated with the phenotypic plasticity of canola. When grown under these conditions, plants are stimulated to occupy the physical space available and potentialize the interception of photosynthetically active radiation (PAR), resulting in a more significant emergence of lateral branches (Krüger et al., 2011b).

In the absence of surface drainage (ASD), a quadratic response was only observed in 2019, with a number of branches (14.5) at 0.43 m spacing (Figure 2f). From this perspective, the decrease in lateral branch emergence in spacings from 0.43 to 0.68 m in the ASD treatment could be associated with limitations in plant reserves due to the lower nutrient uptake capacity and remobilization for different plant parts. Under anoxic soil conditions, anaerobic catabolism becomes a major drain on nutrient reserves during the generation of chemical energy (Liu et al., 2020).

The increase in soil waterlogging, either due to rainier years with more frequent water table rise (2018) or the absence of drainage structures (ASD), interferes with branch emergence. Under anoxic conditions, leaf abscission caused by the increased concentration of ethylene (Silveira et al., 2014; Loreti, Veen, & Perata, 2016) reduces apical dominance in response to reduced auxin production (Batista-Silva et al., 2019), responsible for the regulatory effect on the action of cytokinin, associated with cell expansion in lateral branching (Barrera-Rojas et al., 2020). According to Ploschuk, Miralles, Colmer, Ploschuk, and Gabriel (2018), plants tend to show a significant emergence of new structures after waterlogging stress, especially tertiary and quaternary branches as well as new leaves.

The number of pods per plant was influenced both by the presence of drains and the modification of the spacing between sowing rows. In 2018, the PSD system showed the highest number of pods at the 0.43 m spacing, resulting in 139 pods per plant. In the absence of drains, a linear increase of 1.8 pods was observed for every 0.10 m increase in spacing, totaling 24 pods per plant at 0.68 m (Figure 3a). The decrease in the number of pods per plant in the absence of drainage could be directly related to the abscission of leaves, flowers, and siliques under the deleterious effect of physiological plant changes, such as the increased concentration of ethylene due to soil anoxia (Silveira et al., 2014; Wollmer, Pitann, & Mühling, 2018).

In the second year of cultivation, the use of drains resulted in a 205.0% higher number of pods per plant in relation to the ASD treatment, totaling 85.5 pods of difference (Figure 3c). Similar results were obtained by Santos (2020) in waterlogged lowlands in different cultivation years as the number of pods per plant was reduced by 29.9 to 50.3% in the absence of drainage. The present data is corroborated by the results obtained by Li et al. (2016) in waterlogged soils. When evaluating the resistance of different canola genotypes, the number of pods per plant reduction ranged from 32.0 to 78.1%.

The row spacing data for 2019 fit a quadratic model, and the 0.48 m spacing resulted in the highest number of pods per plant (138). However, several studies obtained a positive linear effect in the absence of water table rise conditions. Krüger et al. (2011a), studying changes in plant spacing for the joint analysis of different population densities, including 40 plants m^{-2}, observed a 59.9% increase in the number of pods per plant when changing plant spacing from 0.20 to 0.60 m, and obtained 331 pods per plant.

Bandeira et al. (2013) also observed an increase from 271.6 to 339.7 in the number of pods per plant when changing plant spacing from 0.17 to 0.68 m, although in a joint analysis for the densities of 15, 30, 45, and 60 plants

m^{-2}. From this perspective, the changed response of drained environments could be associated with higher branch emergence at wider spacings (Figure 2e and f). The higher structural energy expenditure in branches is capable of reducing the plant energy required for the generation of more pods and grains at wider spacings.

The number of seeds per pod was higher in the presence of drains and in the spacing between rows of plants of 0.17 m in both crop years. This parameter was reduced by 130.8 and 26.5% in the absence of surface drainage compared to the PSD treatment in 2018 (Figure 3d) and 2019 (Figure 3f), respectively. The results obtained by Xu et al. (2015) corroborate the present study on a waterlogged environment flooded for seven days during anthesis, which recorded a 24.3% decline in the number of seeds per pod. Li et al. (2016), testing waterlogged-tolerant genotypes, observed that flooding resulted in a mean 7.0% reduction in the number of seeds per pod of canola.

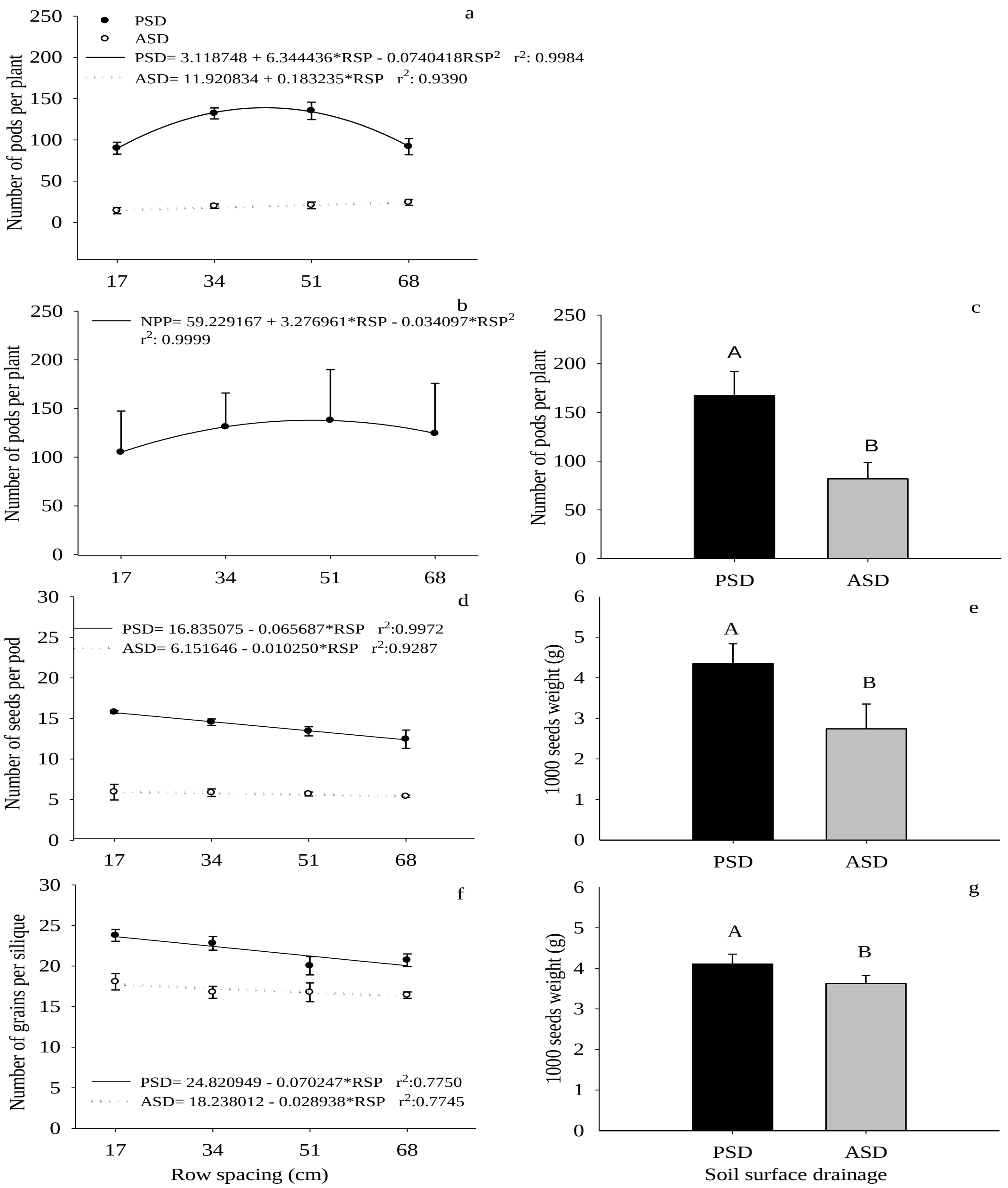

Figure 3. Number of pods per plant (a, b, c), number of seeds per pod (d, f), and 1000 seeds weight of canola (e, g) grown in soils of absence (ASD) and presence of surface drains (PSD) and under row spacing variation (RSP) in the 2018 (a, d, e) and 2019 crop years (b, c, f, g).

Surface drains mitigate the effects caused by soil anoxia, favoring lower root mortality, increasing the photosynthetic capacity of plants and the availability of energy reserves, and improving the pollination and fertilization rates of flower stigmas (Liu et al., 2020). Therefore, surface drainage in flooded environments can increase the crop yield and allow sowing in areas influenced by waterlogging periods even in years such as 2018, with longer soil water saturation and conditions of probable soil anoxia.

The decrease in the number of seeds per pod at wider spacings could be directly related to the partition of photoassimilates for vegetative growth, branching, and the maintenance of the LAI instead of being summarily used for flowering and seed filling. Moreover, Kirkegaard, Lilley, Brill, Ware, & Walela (2018) emphasized that the self-shading which occurs as a result of increased plant density could also negatively affect the number of seeds per pod, resulting in a mean of seeds per pod reduction of up to 48.0% in canola-growing areas in southern Australia under partial and total shading.

The one thousand seeds weight variable was affected by the introduction of soil surface drainage in canola cultivation. In PSD, it was 58.7% (2.74 g) and 13.3% (4.10 g) higher compared to the ASD treatment (Figure 3e and g) in 2018 and 2019, respectively. Therefore, the one thousand seeds weight values in PSD are similar to those of canola cultivation in non-waterlogged soils, such as the 4.1 g value observed by Bagheri et al. (2011), 3.6 g by Krüger et al. (2011a), and 3.0 to 3.5 g by Botegga et al. (2020). According to Liu et al. (2020), the anaerobic catabolism under anoxia is another carbohydrate drain on the plant to the detriment of energy synthesis. Associated with this, the authors mentioned that the emergence of new reproductive structures under the effect of waterlogging in ASD conditions, further restricts the availability of reserves to be translocated into grains compared to PSD.

In grain yield, the modification of the spacing between sowing rows as well as the insertion of drains influenced the productive capacity of canola, both in 2018 (Figure 4a) and 2019 (Figure 4b). In the two experimental years, the PSD condition showed higher yield values than ASD. In 2018, the grain yield had a quadratic response both in the PSD and ASD conditions. In PSD, the maximum grain production efficiency adjusted by the model with the 0.41 spacing was estimated at 1,237.3 kg ha^{-1} or 10.7 times higher than in the ASD treatment, in which the maximum yield obtained with the 0.46 m spacing was 118.8 kg ha^{-1}.

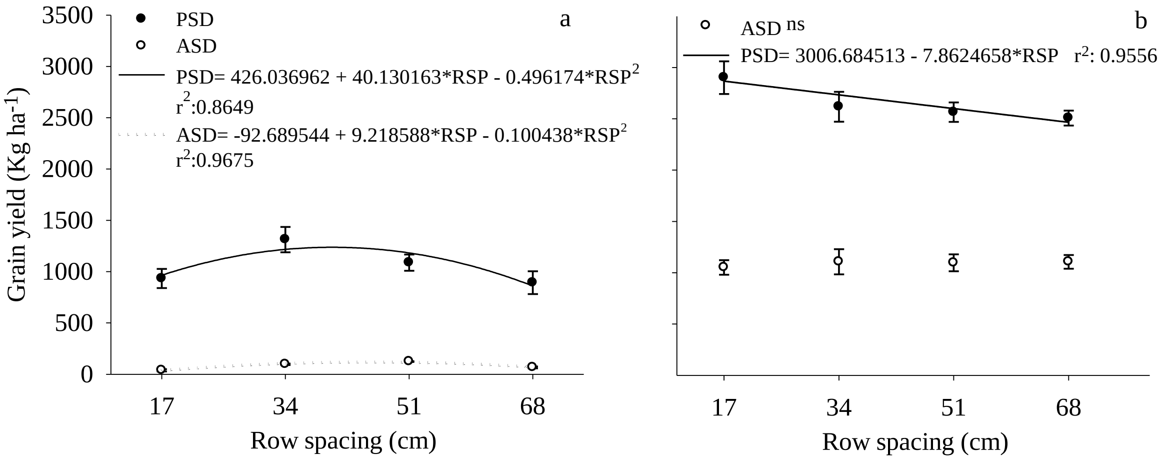

Figure 4. Canola grain yield (a, b) subjected to row spacing variation in environments with presence (PSD) and absence of surface drainage (ASD) in 2018 (a) and 2019 (b). (ns: non-significant at 5% probability by the Scott-Knott test; r^2: coefficient of determination).

In 2019, the greatest decrease in plant density and number of seeds per pod, associated with increased intraspecific competition in the row, negatively affected the grain yield, with a linear reduction in the PSD treatment (Figure 4b). The 0.17 m spacing resulted in the highest grain production (2,901.1 kg ha^{-1}), increasing this parameter by 15.7% in relation to the widest spacing of 0.68 m. The mean yield with ASD was 1,090.2 kg ha^{-1}, representing only 37.6% of the highest yield obtained with the 0.17 m spacing and PSD.

Grain yield reduction with row spacing modification was also observed by Chavarria et al. (2011), who recorded 2,600.0 kg ha^{-1} with a spacing of 0.17 m. Using the same row spacing, Bandeira et al. (2013) harvested 1,041.3 kg ha^{-1} grains, decreasing to 576.7 kg ha^{-1} when the spacing was changed to 0.68 m. Krüger et al. (2011a) and Krüger et al. (2014) obtained 1,381.0 and 969.0 kg ha^{-1} with a spacing of 0.20 m, decreasing to 848.0 and 834.0 kg ha^{-1} when the spacing was changed to 0.60 m. There is a significant disparity in the literature with regard to the grain yield of canola subjected to row spacing variation, as evidenced by the results obtained in 2018 and 2019. The different grain yields observed indicate that canola is strongly affected by the environment, crop management, and genotypes used for cultivation, while waterlogging is a limiting factor that needs to be minimized.

Several studies have also found significant results in response to the deleterious effect of high soil moisture on grain yield under waterlogging conditions. Zou et al. (2014) and Nabloussi et al. (2019) observed yield losses of 50.0

and 56.0% in Asia. In southern Brazil, Santos et al. (2020) observed grain yield reductions of 194.9 kg ha^{-1} in soils without the removal of excess surface and subsurface water, whereas the use of drains increased the canola grain yield by 126.9%. Therefore, the drainage of excess surface water is essential to mitigate the adverse effects of rainy periods on canola-growing areas in poorly drained soils (Goulart et al., 2020).

The PSD treatment results revealed that there was more grain yield in 2019 than in 2018, which could be associated with the different environmental conditions to which the crop was exposed in the two years. In 2018, the intense waterlogging associated with the lower availability of solar radiation during stem elongation and grain filling may have directly reduced the accumulation of plant reserves, as0 observed by Liu et al. (2020). Moreover, the increased production of new vegetative structures, such as branches, limited the assimilates available for the production of more pods with grains. In 2019, the reduction in water table elevation periods coupled with the reduced number of branches, higher plant density, and higher plant height in relation to 2018 may have favored the increase in grain yield. When studying the effect of elongation in different subperiods of canola development, Ploschuk, Miralles, and Striker (2021) observed greater potential damage during anthesis, with grain yield losses ranging from 42.0 to 69.0% as opposed to 17.0 and 30.0% observed in the vegetative period.

The highest grain yield values obtained in the PSD treatment, 1,056.1 and 2,901.1 kg ha^{-1} in 2018 and 2019, respectively, are encompassed by the fluctuation of results observed among commercial crops cultivated in southern Brazil. From this perspective, the expansion of canola cultivation into lowlands could be an alternative to obtain grain yields as satisfactory as those obtained in high lands, especially due to the idle periods of farmable areas, as long as surface drainage is performed to remove the excess water. The 2019 crop year stood out due to its production superiority in relation to the regional average of canola grain production, indicating the existence of years with high production potential for canola cultivation in lowlands when using appropriate cultivation techniques, such as soil surface drainage.

Conclusion

The use of surface drains in waterlogged environments decreases the emission rate of compensatory lateral branches, increases the plant height, number of pods, seeds per pod, and seeds mass, resulting in higher canola grain yields. In the absence of waterlogging in canola cultivation, the smallest spacing between rows (0.17 m) increased the number of seeds per pod and the grain yield. However, in waterlogged environments, the spacing 0.45 m between plant rows resulted in more pods and higher grain yields. The expansion of canola cultivation into waterlogged lowlands has technical viability in the presence of surface drainage.

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