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Soil compaction and drought stress on shoot and root growth in crambe (*Crambe abyssinica)*

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Abstract

This study investigated the effects of soil compaction and irrigation management on shoot and root growth in crambe. Two experiments were conducted in a heated greenhouse. Experiments were arranged in a completely randomized design, in a factorial, with two irrigation treatments (well-irrigated or drought stress conditions, imposed at the flowering and grain filling stages) and six soil bulk density levels (0.90, 0.99, 1.08, 1.17, 1.26, and 1.35 Mg m^{-3}), with four replicates. The restriction of the water supply during the stages of flowering and grain filling affects the growth and productivity of crambe. The roots of the crambe plant are not significantly affected by drought conditions or the interaction between drought conditions and soil compaction. Crambe shoot growth was not significantly affected by soil compaction, at soil densities up to 1.35 Mg m^{-3}. Crambe is more sensitive to drought conditions than to soil compaction.

Keywords: *Crambe abyssinica*; industrial crop; irrigation management; oilseed; soil bulk density.

Introduction

The ability of plants to obtain water and nutrients from the soil is related to their capacity to develop extensive root systems. Compacted soil layers may restrict deep root growth and adversely affect plants' ability to access subsoil water during the growing season. This is especially true in the fall and winter when soils are relatively dry due to the seasonally limited rainfall in tropical savanna regions like the Brazilian Cerrado. Therefore, the deleterious effects of soil compaction on crop yields can be worsened by drought stress, especially in years with little rainfall. Buttery et al. (1998) found that limited root penetration in compacted soils aggravated the economic effects of drought by further reducing soybean yield. Root elongation occurs when root growth pressure is higher than soil impedance, which depends on soil structure and management (Calonego and Rosolem, 2010). The natural path for root growth is through macro-pores, or voids that occur between soil aggregates. These are almost always connected to each other in soils with no compaction problems. Vepraskas (1994) reported that soils with a high proportion of aggregates larger than 2.0 mm, and consequently higher macroporosity, have 30% more maize roots per unit depth. According to Calonego and Rosolem (2010), however, a mere decrease in root elongation cannot be considered a reduction in root growth. This is because when roots face a high resistance layer there is an intense proliferation of fine lateral axes, and the spatial distribution of the root system is modified, instead of its total length. This may contribute to an increase in root specific surface and soil exploration. Therefore, when the growing root system reaches a compacted layer in the subsoil, there is an over-proliferation of roots in the uppermost soil layers (Rosolem et al., 2002), but growth in the subsoil is limited. Consequently, the water and nutrient supply to the plants may be impaired and crop yields decreased (Chen and Weil, 2011). Soil water content influences the aeration, temperature, and mechanical resistance of the soil, factors which are also affected by soil bulk density and pore size distribution (Reichert et al., 2003). An increase in water content decreases both soil aeration and soil resistance to root penetration. The first effect is undesirable, whereas the second is desirable (Letey, 1985). These soil physical factors may interact and regulate root growth and function, based on critical limits associated with air, water, and soil resistance, and ultimately affecting the growth and yield of crops. However, crops and cultivars respond differently to soil compaction depending upon the characteristics of their rooting systems (Guimarães et al., 2002). Several studies have been conducted using compacted PVC rings to determine the annual species tolerance to soil compaction. With regard to plant growth at different soil bulk densities, studies carried out on soybean (Beutler and Centurion, 2003), maize (Foloni et al., 2003), cotton (Falkoski Filho et al., 2013), cover crops (Rosolem et al., 2002; Foloni et al., 2006) and crambe (Silva et al., 2012) showed that in most cases, the effects of soil compaction on the development of both shoot and rooting system of plants are damaging. However, there are no studies that relate the effects of soil compaction and water availability to the growth of crambe. Crambe (*Crambe abyssinica* Hochst.) is a multipurpose oilseed crop with great potential to become one of the most economically important crops in Brazil. It is used

Table 1. Plant height, stem diameter, and shoot dry matter of crambe plants under well-irrigated conditions or drought stress conditions, imposed at the flowering and grain filling stages.

Irrigation	Plant height (cm)		Stem diameter (cm)		Shoot dry matter (g plant^{-1})	
	2012	2013	2012	2013	2012	2013
Well-irrigated	89.91	66.61 a	0.508	0.37 a	2.20	0.83
Stress conditions	88.32	61.16 b	0.501	0.34 b	1.94	0.83

Means followed by the same letter in the column do not differ by Tukey's test ($p \leq 0.05$). Means without letters in columns indicate no significance by Tukey's test ($p \leq 0.05$). Means without letters in columns indicate no significance by Tukey's test ($p \leq 0.05$).

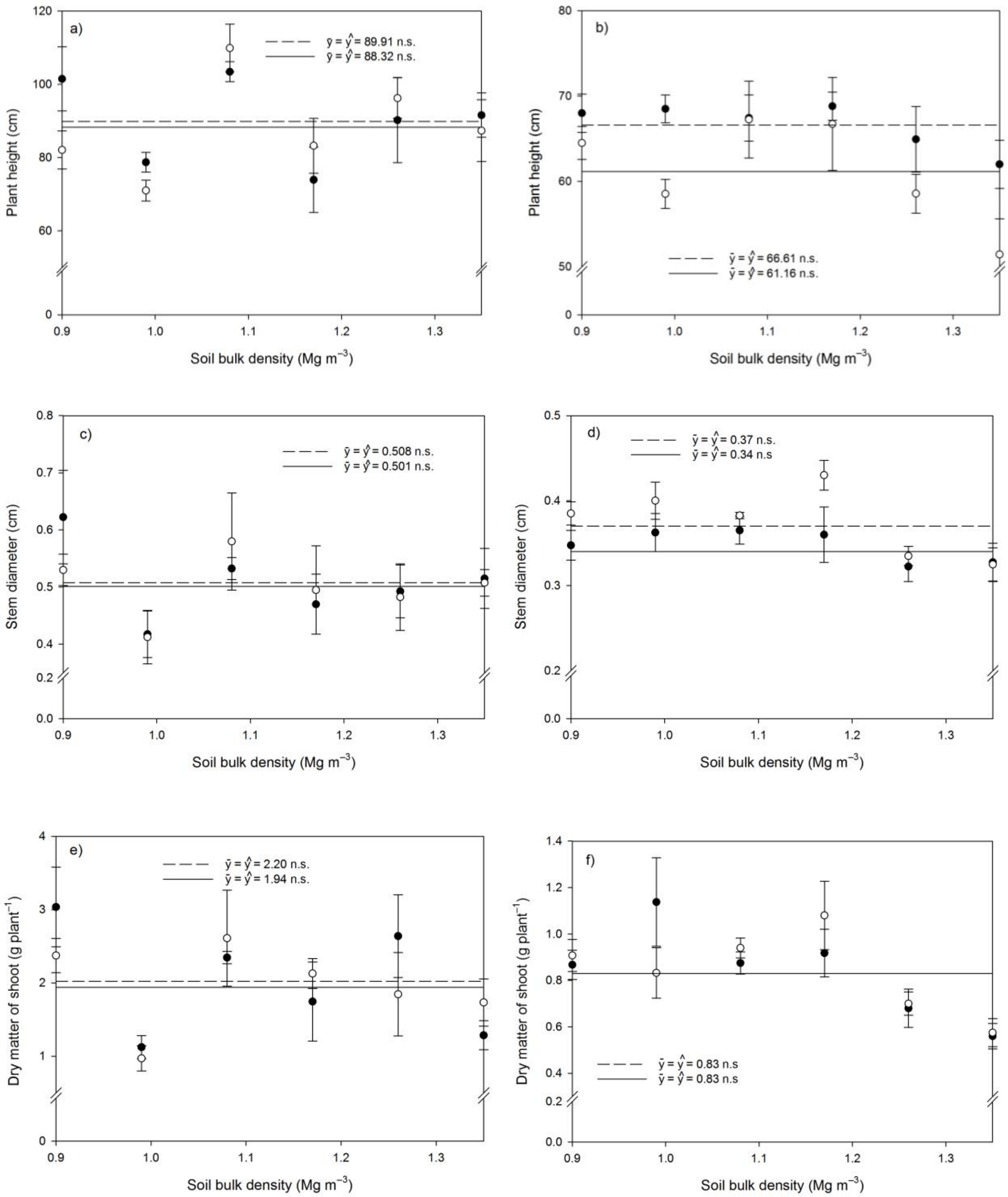

Fig 1. Plant height in 2012 (a) and 2013 (b); stem diameter in 2012 (c) and 2013 (d); shoot dry matter in 2012 (e) and 2013 (f) of crambe plants under well-irrigated conditions (---) or drought stress conditions, imposed at the flowering and grain filling stages (—), as affected by soil bulk density. n.s. = not significant at 5% by F-test. Vertical bars (where bigger than the symbols) show the standard error.

for many purposes: industrial (i.e., manufacture of plastic bags and transmission fluid), as a cover plant and rotation crop, and for the production of biodiesel. According Pitol et al. (2010), its aggressive root system makes it resistant to drought. However, Silva et al. (2012) found that increasing the soil bulk density from 1.14 to 1.58 Mg m^{-3} negatively affected the root growth of crambe plants. These contradictory results indicate a eed for further research. An improved understanding of crambe's tolerance to soil compaction level and drought is essential for the development of competitive strategies for improving crop production. This study investigates the effects of soil compaction and irrigation management on the shoot and root growth of crambe.

Results and Discussion

Irrigation management

The restriction of the water supply during flowering affected ($p \leq 0.05$) crambe plant height, stem diameter, shoot dry matter, number of seeds per pot, and yield (number of grains) in 2013 (Experiment 2). In 2012, there was increased shoot growth and grain yield of crambe under well-watered conditions, however, due to variability in the dataset, the effect was not significant ($p \leq 0.05$). In this study, drought stress was not significantly affected by soil compaction (Table 1 and 2).

According Pitol et al. (2010), crambe is a species that has a taproot, and is drought tolerant after germination and establishment. However, if drought stress occurs after 50 days (during flowering) it will affect the development of crambe in general. Similar results were observed in other species, as Santos et al. (2012) found when working with wheat, a crop that is sensitive to drought stress. They observed a reduction in plant height and shoot dry matter due to the restriction of the water supply at the start of flowering. Similarly, Beutler and Centurion (2003) found that the lower water content of the soil (0.05 MPa) resulted in shorter soybean plants compared to those grown under control conditions (0.01 MPa). Zahedi et al. (2011) also observed a decrease in the stem diameter of canola under drought stress conditions. Trautmann et al. (2014) found that soil water content up to 0.1 MPa tension did not affect the shoot dry mass of soybean. Bassegio et al. (2013) observed that the growth of oilseed flax suffers under drought conditions. Seeds per pot and yield (g pot^{-1}) of crambe grown under drought conditions was lower in both experiments, however, the effect was only significant in experiment 2 (2013). This is due to the variability of the data from the first year, as there is only a single species of crambe in Brazil with little genetic improvement. Sanchez et al. (2014) found that rapeseed, which belongs to the same family as crambe, produced more grain under well irrigated conditions. Bilibio et al. (2011) and Bilibio et al. (2014), with experiments in Germany and Brazil respectively, also observed that rapeseed is sensitive to drought conditions, the main effect of which is decreased grain yield. Medeiros et al. (2005) found that water availability was more limiting to the yield of rice grains than soil compaction, as observed in this study. Sousa and Lima (2010) evaluated the effects of drought stress on common bean crops at different vegetative stages of plant development (vegetative, pre-flowering, flowering, grain filling, or ripening), and found that water restriction after the grain filling and ripening stages had the least effect on crop yield. Therefore, like rapeseed, crambe has also been shown to be a crop sensitive to drought conditions. Although shoot growth increased, when crambe was grown in well-watered conditions, root dry matter and root length density were not affected by soil compaction (Table 2). Junior Ramos et al. (2013) observed that the root dry mass of oats was not affected by the reduction of the available water in the soil. Guimarães et al. (2011) observed that the shoot biomass of upland rice cultivars was positively correlated with root density under drought conditions.

Soil compaction

The shoot and root growth of crambe were not significantly affected ($p \leq 0.05$) by soil bulk density in either experiment. Soil compaction up to a bulk density of 1.35 Mg m^{-3} did not affect plant height (Figs 1a and 1b), stem diameter (Figs 1c and 1d), or the dry matter of crambe (Figs 1e and 1f). One possible explanation for this is that the level of compaction at 1.35 Mg m^{-3} did not impair crambe growth, since the species has an aggressive root system. Silva et al. (2012) also found that the height of crambe was not affected by an increase in soil bulk density from 1.14 to 1.58 Mg m^{-3}. However, increasing the soil bulk density did progressively reduce the height of soybean plants (Beutler and Centurion, 2003), cotton, and maize (Silva et al., 2006). Increasing soil bulk density also did not affect the shoot dry matter of crambe (Silva et al., 2012), soybean (Rosolem et al., 1994), or cover crops (Rosolem et al., 2002). Neither the number of seeds per pot (Figs 2a and 2b) nor the yield (Figs 2c and 2d) was affected by soil compaction. The shoot development of crambe was not influenced by the combination of bulk density and restriction of the water. The scientific literature is mostly silent on the subject of crambe, especially with respect to studies on the interaction between the management of water in the soil and soil compaction in crambe. Silva et al. (2012) evaluated the effect of soil compaction on the development of crambe, but only until the flowering stage and only on the aerial parts. Secco et al. (2009) reported reductions in wheat yield under high soil compaction levels. Gubiana, Reichert and Reinert (2014), who investigated the interaction of water availability and soil compaction in the field, did not consider interactions between factors (14% probability). However, increased water availability in the soil scattered the losses of more yield compression grains than in bean growth. However, the interaction between compression and water levels was studied by Beutler and Centurion (2003; 2004), who evaluated the root growth and grain yield of both soybeans and rice, growing in pots. The root dry matter of crambe was not affected by soil compaction (Fig 2e). Silva et al. (2012) observed that increasing levels of soil compaction linearly decreased the root dry matter of crambe in and below the compacted layer. Falkoski Filho et al. (2013) found that soil bulk densities from 1.20 to 1.60 Mg m^{-3} (i.e., 0.5 to 1.9 MPa) resulted in a 50% reduction in root growth in cotton cultivars. Deleterious effects of soil compaction on root growth are usually reported in the literature, as has been the case for soybean (Rosolem et al, 1994), maize (Foloni et al, 2003), forage turnip (Reinert et al., 2008), and various cover crops (Rosolem et al., 2002).

Under drought stress conditions, the root length density was significantly affected by soil compaction levels (Fig. 2f). Falkoski Filho et al. (2013) found that the lowest values of the root length density of cotton cultivars occurred in soil with bulk densities of 1.50 Mg m^{-3} or 1.8 MPa. Silva et al. (2006) observed that an increase in soil bulk density of 1.0 to 1.5 Mg m^{-3} resulted in a 27% reduction in water consumption by maize and soybean, a 24% reduction for signal grass (*Brachiaria brizantha*), and a 52% reduction for cotton.

Table 2. Seeds per pot, yield, root dry matter, and root length density of crambe plants under well-irrigated conditions or drought stress conditions, imposed at the flowering and grain filling stages.

Irrigation	Seeds per pot		Yield ($g\ pot^{-1}$)		Root dry matter ($g\ pot^{-1}$)	Root length density ($cm\ cm^{3}$)
	2012	2013	2012	2013	2013	2013
Well-irrigated	185.2	103.9 a	1.25	0.73	0.48	0.0804
Stress conditions	138.70	81.0 b	0.91	0.46	0.45	0.0801

Means followed by the same letter in the column do not differ by Tukey's test ($p \leq 0.05$). Means without letters in columns indicate no significance by Tukey's test ($p \leq 0.05$). Means without letters in columns indicate no significance by Tukey's test ($p \leq 0.05$).

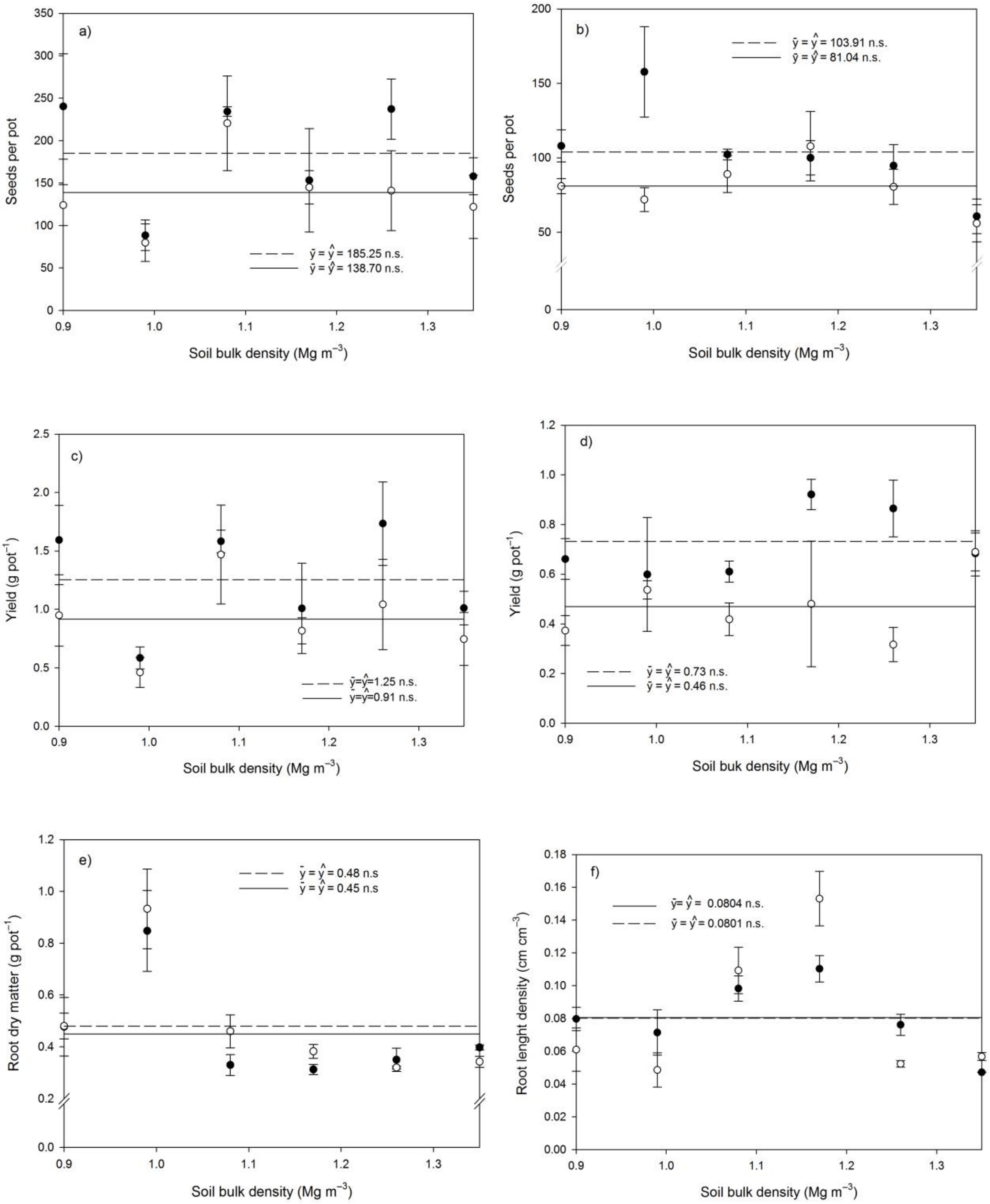

Fig 2. Seeds per pot 2012 (a) and 2013 (b); yield in 2012 (c) and 2013 (d); root dry matter in 2013 (e) and root length density in 2013 (f) of crambe plants under well-irrigated conditions (---) or drought stress conditions, imposed at the flowering and grain filling stages (—) as affected by soil bulk density. n.s.: not significant at 5% by F-test. Vertical bars (where bigger than the symbols) show the standard error.

However, the high degree of variation in the evaluated variables should be emphasized. Such inferences may be related to high genetic variability in this cultivar. Lara et al. (2013) reported the existence of high genetic variability in the cultivar FMS Brilhante across all morphological characteristics.

Therefore, further studies are needed to evaluate the interaction between soil compaction and irrigation management, since during periods of drought, access to water is limited. This is because the dry and compacted soil is highly resistant to root penetration (Clark et al., 2003), and thus does not allow for the use of water stored in the layers of the soil below the highest resistance layer.

Material and methods

Plant materials

The crambe (*Crambe abyssinica* Hochst. Former. RE Fries) cultivar used was FMS–Brilhante, which originates from the Foundation Mato Grosso do Sul, MT, Brazil (FMS).

Study site description

The two experiments were carried out at the State University of West Paraná in Cascavel, Brazil (24º53'47" S, 53º32'09" W, and altitude of 780 m), from September 2012 to December 2012 (Experiment 1), and in 2013 from April to August (Experiment 2). Experiments were conducted in an air-heated greenhouse, where the environmental conditions were as follows: mean air temperature of 25 ± 5 ºC, and mean air relative humidity of 80%.

The soil used in the experiment was collected at depths of 0.0–0.60 m from a very clay-rich Rhodic Hapludox (Dystroferric Red Latosol in the Brazilian classification), then passed through a 4.0 mm screen. Soil chemical analysis showed a pH in $CaCl_2$ of 4.9, 22 g dm^{-3} of organic matter, with 5 mg dm^{-3} of P (Mehlich-1), 7.4 $cmol_c$ dm^{-3} of H + Al, 0.4 $cmol_c$ dm^{-3} of K, 5.3 $cmol_c$ dm^{-3} of Ca, 3.2 $cmol_c$ dm^{-3} of Mg, CEC of 16.4 $cmol_c$ dm^{-3}, and a base saturation of 55%. All the soil chemical properties were analyzed according to methods described by Embrapa (2009). Particle size analysis was performed by the pipette method (Embrapa, 1997) and the values obtained were 720 g kg^{-1} clay, 150 g kg^{-1} silt, and 130 g kg^{-1} sand.

Experimental design and treatments

The experiments were arranged in a completely randomized design, in a factorial, with two irrigation treatments (growth under well-irrigated or drought stress conditions, imposed at the flowering and grain filling stages) and six soil bulk density levels (0.90, 0.99, 1.08, 1.17, 1.26, and 1.35 Mg m^{-3}), with four replicates. Pots were built using four PVC rings with an internal diameter of 20 cm, one on top of the other. The upper ring was 20 cm high. The three bottom rings were each 15 cm high, and were where the compaction treatments were applied. All rings were filled with 15 cm of soil. Soil water content was raised to 140 g kg^{-1}, and appropriate volumes of soil were packed into the PVC rings to reach bulk densities of 0.90, 0.99, 1.08, 1.17, 1.26, and 1.35 Mg m^{-3}. The bulk density in the upper rings was 0.90 Mg m^{-3} (loose soil and sieved through a 4.0 mm mesh). These densities were based on results obtained by Tormena et al. (1999), who proposed a critical soil density from 1.25 to 1.30 Mg m^{-3} for very clay rich soils. Ten crambe seeds (*Crambe abyssinica* Hochst, cv. FMS Brilhante) were sown in each pot, and three days after seedling emergence, they were thinned to four plants per pot. Up to the flowering and grain filling stages (65 days after plant emergence), all crambe plants were grown under well-irrigated conditions. Subsequently, the differentiation of treatments under drought stress was begun by initiating restriction of the water supply. Irrigation was carried out according to the Evapotranspiration (ET) Method. Volumes of water replacement were based on estimates of the amount water evapotranspirated (measured by an evaporimeter), and periodically adjusted by multiplication of a crop coefficient (Kc). As there is no applicable information available for crambe, this study used the Kc of forage turnip (*Raphanus sativus*) as proposed by Fietz et al. (2008). The turnip belongs to the same family as crambe (Brassicaceae) and has a similar growth cycle. Crop coefficient (Kc) is the ratio between crop evapotranspiration (ETc) and the reference evapotranspiration (ETo) value obtained by a meteorological station, and is calculated using the following equation: Kc = ETc / ETo. The Kc changes during the growing season in order to reflect changes in the size of the plants; large plants use more water than small plants, so Kc increases as the crambe grows.

Sampling components production

At maturity (95 and 110 days after plant emergence in Experiment 1 and 2, respectively), crambe yield was evaluated in terms of shoot dry matter (g $plant^{-1}$), root dry matter (g pot^{-1}), and yield (g pot^{-1}). Plants of all treatments were harvested separately, dried for four days at 65 ºC, and then weighed. The shoot length was measured (cm $plant^{-1}$) using a meter scale. Stem diameter at the 1.0 cm base height was measured (cm) using a digital paquimeter. The number of seeds per pot was counted. Root length density was obtained by dividing the root length (cm) by the root volume (cm^3) (Taylor, 1986). Root evaluation was performed only in the second experiment.

Statistical analysis

Original data were subjected to analysis of variance (ANOVA), and the means of water regimes were compared by F test at the 0.05 level of confidence. For the levels of soil compaction, regression analysis and significant equations were used, with adjustment of the greatest determination coefficients ($p \leq 0.05$). All analyses were performed using SigmaPlot 11.0 software for Windows (Systat Software, Inc., San Jose, CA, USA).

Conclusions

The restriction of the water supply during the stages of flowering and grain filling significantly affected the growth and productivity of crambe. Roots of crambe are not significantly affected by drought conditions. Crambe is not significantly affected by the interaction of drought conditions and soil compaction. The shoot growth of crambe was not significantly affected by soil compaction of densities under 1.35 Mg m^{-3}. Crambe is more sensitive to drought conditions than to soil compaction.

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