Root and shoot growth in safflower as affected by soil compaction

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Abstract

Soil compaction, induced by no-tillage practices, can negatively impact soil properties important for plant growth. Compacted soils can restrict root growth depth, resulting in reduced crop yield. Although safflower (*Carthamus tinctorius*) has a deep root system, yield may still be affected by soil compaction. Therefore, this study aimed to evaluate safflower root and shoot growth when submitted to soil compaction in an Oxisol soil under controlled (greenhouse) and field conditions. Five soil bulk density measures were performed in a greenhouse (1.1, 1.2, 1.3, 1.4 and 1.5 Mg m^{-3}). Four compaction levels (established by the number of passes of a farm tractor: 0, 1, 3, and 5 passes consecutively) were performed to evaluate the effect of soil compaction in the field. Root and shoot growth were measured after harvesting the plants. Safflower root growth was reduced when soil compaction increased from 1.1 to 1.5 Mg m^{-3} under controlled (greenhouse) conditions. In field conditions, we observed a decrease in root length, and fresh and dry matter in roots and shoots of safflower as the soil compaction increased to 5P (1.28 Mg m^{-3}). The results of our study suggest safflower root and shoot growth can be impacted by soil compaction which could affect crop yield.

Keywords: *Carthamus tinctorius* L.; density; soil compaction; oilseeds.
Abbreviations: SOM_Soil organic matter; BS_Base saturation; P_tractor passes.

Introduction

The demand for biofuel production has increased in more recent times due to a combination of factors; possible exhaustion of oil supplies, resulting in increasing oil prices, and the impacts that fossil fuels have on the environment, namely the green-house effect, are likely drivers. The increased demands on biofuel production have led to the need to be able to produce biofuel seed oil across multiple seasons. Therefore 'alternative' oilseed crops, such as safflower (*Carthamus tinctorius*), which are more tolerant to abiotic stresses characteristic of tropical climates, are now been utilized (Movahedy-Dehnavy et al., 2009, Santos et al., 2018). Safflower oil has high levels of oleic acid (30%) and linoleic acid (70%) and can be used as a feedstock for biodiesel production (Ilkılıç et al., 2011).

In Brazil, safflower is used as an option for the second annual crop (autumn-winter), during a seasonal period which characteristically has irregular rainfall (Santos et al., 2018). Although this species has the potential for cultivation in drier conditions (Lovelli et al., 2007; Santos et al., 2017), its yield may still be affected by other environmental variables such as soil compaction. Soil compaction is one of the main known causes of soil degradation (Roque et al., 2010). It typically occurs as a result of heavy usage of agricultural machinery and equipment (Lima et al., 2013) causing serious limitations on plant development in affected soils.

Compacted soil layers increase overall soil resistance, restricting root penetration and therefore root growth depth of plants, consequently hindering access to groundwater (Chen et al., 2014; Nosalewicz and Lipiec, 2014). Due to root growth restriction, morphological changes such as increased root diameter and formation of twisted roots can occur (Silva and Rosolem, 2001; Sarto et al., 2018; Bassegio et al., 2018). However, species differ in their ability to overcome compacted soil layers, due to differences in soil pore size and root diameter (Rose et al., 2009).

Safflower has a deep root system that can enable this species a higher tolerance when subjected to soil compaction (Feizi et al., 2010). Several studies have been conducted using PVC rings to determine safflower tolerance to soil compaction (Paludo et al., 2017; Paludo et al., 2018; Sarto et al., 2018). However, few studies have investigated the effect of compaction on safflower growth under field conditions. Therefore, this study aimed to evaluate safflower root and shoot growth when submitted to soil compaction in an Oxisol soil.

Results and discussion

Soil compaction under controlled conditions

Soil compaction levels significantly affected (p<0.01) safflower root growth in the controlled (greenhouse) experiment (Fig. 1). Root length, and fresh and dry root matter, was linearly reduced with increasing levels of soil compaction (Fig. 1A, B and C). The observed growth

Table 1. Bulk density (BD), total porosity (TP), macroporosity e microporosity in layers of 0–0.1, 0.1–0.2, and 0.2–0.3 m depth affected by soil compaction by tractor passes (P).

Tractor passes	BD (Mg m^{-3})	TP (%)	Macroporosity (%)	Microporosity (%)
		Layer 0–0.1 m		
0 P	1.23 a	49.12 a	13.19 a	35.94 a
1 P	1.30 a	46.02 a	10.04 b	35.98 a
3 P	1.34 a	44.57 a	9.52 b	35.05 a
5 P	1.32 a	45.56 a	9.71 b	35.85 a
		Layer 0.1–0.2 m		
0 P	1.17 a	54.46 a	9.39 a	45.07 a
1 P	1.20 ab	53.24 ab	9.96 a	43.28 a
3 P	1.22 ab	52.34 ab	9.97 a	42.37 ab
5 P	1.28 b	50.03 b	11.12 a	38.91 b
		Layer 0.2–0.3 m		
0 P	1.13 a	58.42 a	11.17 a	47.25 a
1 P	1.18 ab	56.59 ab	10.09 a	46.49 a
3 P	1.24 b	54.50 b	13.26 a	41.24 b
5 P	1.25 b	53.55 b	10.24 a	43.50 ab

Values represented by the different letters, in each column show significant differences (Tukey test, $P < 0.05$).

Table 2. Root length, root fresh matter, root dry matter, shoot fresh matter and root dry matter of safflower as affected by soil compaction by tractor passes (P).

Tractor passes	Root length (cm)	Root fresh matter (g)	Root dry matter (g)	Shoot fresh matter (g)	Shoot dry matter (g)
0 P	11.60 a	3.06 a	1.40 a	34.69 a	10.53 a
1 P	5.76 b	2.56 a	1.23 ab	33.36 a	10.22 a
3 P	3.54 c	3.17 a	1.32 a	22.11 b	6.45 b
5 P	2.92 c	2.32 a	0.87 b	20.24 b	5.76 b

Values represented by the different letters, in each column show significant differences (Tukey test, $P < 0.05$).

Table 3. Soil chemical characteristics in the experimental areas before initiating the experiment.

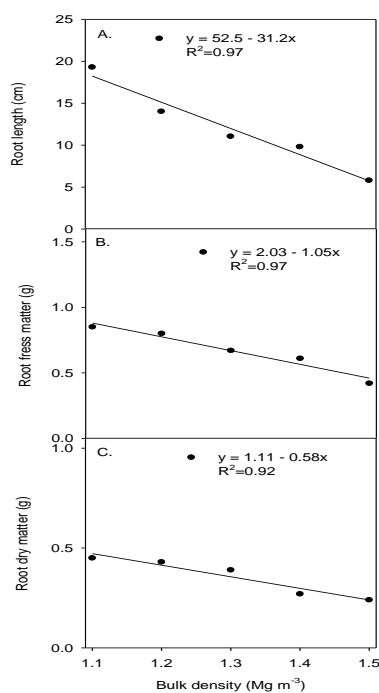| pH (CaCl$_2$)	SOM†	P (resin)	H + Al	Exchangeable K	Exchangeable Ca	Exchangeable Mg	BS‡
	g dm^{-3}	mg dm^{-3}	———————cmol$_c$ dm^{-3}———————				%
5.0	32	9.4	6.2	0.33	5.2	2.9	58

† Soil organic matter.‡ Base saturation.

Fig. 1. Root length (A), root fresh matter (B) and root dry matter (C) of safflower affected by soil bulk density. Significant at $P < 0.05$ probability.
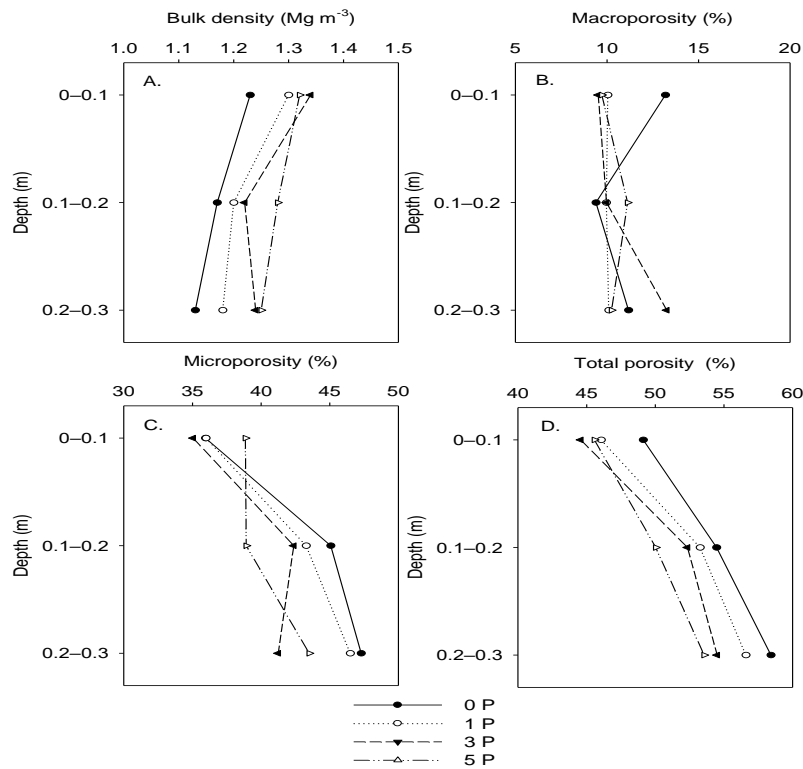
1444

Fig 2. Bulk density (A), macroporosity (B), microporosity (C) and total porosity (D) affected by tractor passes (P).

Fig 3. Safflower root architecture affected by soil compaction. P = Tractor passes (0, 1, 3, and 5).
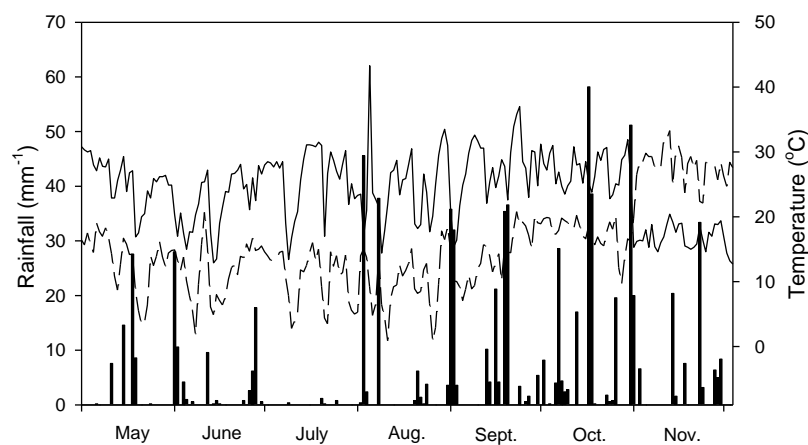

Fig 4. Behavior of meteorological variables of precipitation and mean temperature during safflower cultivation.

reduction suggests deep root growth was restricted in more compacted soil conditions (Sarto et al., 2018). This result is in keeping with the research findings of Reichert et al. (2009), which showed soil density values >1.35 Mg m^{-3} for clayey soils, restrict root growth of some agricultural crops. Compacted soils often cause a reduction in root growth due

to a reduced volume of soil been utilized by the plants root system, aerial growth and development of the plant can be negatively affected as a result (Rosolem et al., 2002; Sarto et al., 2018).

In order to adapt to increased penetration resistance levels in compacted soils, the plants roots undergo morphological

and physiological changes that vary depending on the species, or genotype of the plant (Materechera et al., 1992). Other studies have shown similar findings; maize in a medium texture Distroferric Red Latosol soil (1.28 to 1.68 Mg.m^{-3}) (Foloni et al., 2003), and soybean in a clay-textured Red Nitosol soil (0.26 to 1.98 MPa) (Foloni et al., 2006) demonstrated root dry matter effects specific to cultivar or genotype.

These results corroborate the findings of a study by Sarto et al. (2018) that investigated different safflower genotypes submitted to varying soil densities; with an increase in density there was a reduction in the values of root dry matter obtained, and this reduction was more significant when the soil density was 1.6 Mg m^{-3}. Interestingly, in another study investigating different genotypes of safflower in compacted soils the critical soil density level for crop growth was, on average, 1.2 Mg m^{-3} (Paludo et al., 2017). The authors also found that the observed differences appeared to vary between genotypes.

Soil compaction under field conditions

Significant differences ($p < 0.05$) were found between macropores in the 0–0.1 m soil layer. Macropore volume was significantly higher in uncompacted soil (0P = 13.10%) compared to compacted soil treatments (1P = 10.04%, 3P = 9.52% and 5P = 9.71%) (Table 1; Fig. 2B). In a study by Junior et al. (2012) investigating the effects of different compaction levels on latosol soil, soil density values increased with increased tractor passes. The researchers also found there was a reduction in macroporosity in the 0–0.1 m soil layer.

Notably, significant difference ($p < 0.05$) was observed between the different soil treatments in the 0.1–0.2 m layer for the current study. Was observed an increase in soil density (Fig. 2A), reduction of the total soil porosity (Fig. 2D), and the volume of micropores (Fig. 2C) in the 0.1–0.2 m soil layer when the soil was compacted with 5 tractor passes (5P) (Table 1). This finding contrasts with that of Scapinelli et al. (2016) which found there was a significant difference in the volume of macropores in the 0.10–0.15 m layer after the soil was compacted.

In the 0.2–0.3 m layer, it was observed that the 0P treatment presented lower density values for the 3P and 5P soil treatments (Fig. 2A). There was also a reduction in the values for volume of micropores (Fig. 2C) and the total porosity (Fig. 2D). This suggests the weight of the tractor-sprayer set negatively affected these physical attributes of the soil to a depth of 0.2–0.3 m (Table 1; Fig. 2).

Safflower shoot and root growth was significantly affected ($p < 0.05$) by soil compaction under field conditions. It was observed that root length was reduced in the 1P, 3P, and 5P compacted soil treatments compared to the 0P control (Table 2).

The shorter root length observed in 5P compacted soils had negative effects on root dry matter and fresh and dry matter in roots and shoots (Table 2). Research on safflower genotypes conducted by Paludo et al. (2018) found that the critical soil density value for root dry matter was 1.04 Mg m^{-3}. The authors also found that the measurement of increased soil density was reduced by up to 71% for the total root dry matter. Similar to the current study, decreases observed in the dry matter of shoot accumulation caused by penetration resistance are likely due to root aeration deficiency, which in a clay-textured Red Latosol begins with soil densities close to 1.30 Mg m^{-3} (Argenton et al., 2005; Sarto et al., 2018).

The current field experiment also showed there was a reduction in the average length of safflower roots under different soil compaction treatments (3P= 69% and 5P = 75%; Table 2). These findings are similar to those found by Bergamin et al. (2010); a significant reduction in the growth of corn roots was observed with increasing levels of tractor passes. Another study by Valadão et al. (2015) also found higher traffic levels (8 tractor passes) negatively influenced the root growth of soybeans, as well as their distribution in the soil profile. The authors postulated this was likely owing to soil compaction levels causing an increase in resistance to soil penetration by plant roots. Additionally, it was thought that compaction would cause a reduction in macroporosity and total porosity of the soil. Interestingly, a study by Scapinelli et al. (2016) investigating sunflower growth in compacted soils found that physical soil changes caused by tractor traffic resulted in anatomical changes in the roots of plants after only three tractor passes.

Root restriction and confinement in the topsoil are accompanied by changes to the entire root system (Grzesiak et al., 2013; Pfeifer et al., 2014), as shown in Fig. 3. Compaction causes root thickening due to morphophysiological changes to the radicle system after entering the compacted layer (Ramos et al., 2010).

Materials and methods

Study site description

The controlled experiment was conducted at Western Paraná State University, at the Cascavel-PR campus (24°59'21.2 "S 53°26'59.6 "W; altitude of 781 m), from September to December 2017. This component of the study was undertaken in a green house. The Oxisol soil used in the study was collected from a depth of 0–0.2 m, comprising a clayey to very clayey texture (600 g kg^{-1} of clay, 320 g kg^{-1} of silt and 80 g kg^{-1} of sand) (Embrapa, 1997), a soft undulating relief, and basalt substrate (Embrapa, 2018). Before starting the experiment, the chemical characteristics of the soil were determined (0–0.2 m; Table 3) according to the methods of Embrapa et al. (2009).

Treatments and experimental design

Five soil compaction levels (1.1, 1.2, 1.3, 1.4 and 1.5 Mg m^{-3}) were used in the experiment. The study design was entirely randomized and involved four repetitions for each soil treatment. To prepare the PVC rings for the compacted layer, the mass required to fill the ring was calculated. The soil was then compacted by applying light pressure with an iron cylinder measuring the same internal diameter as the PVC rings (Sarto et al., 2018).

Pots were assembled using overlapping PVC rings with an internal diameter of 0.2 m. The height of the top and bottom rings of the pots were 0.15 m and 0.3 m respectively, and the height of the intermediate ring, in which we placed the different soil treatments, was 0.5 m. Seven saffron seeds were sown per pot to a depth of 0.3 m. Thinning was applied once seedlings were visible, with only three plants kept per pot for the duration of the experiment. Each experimental unit received set irrigation in accordance with the evapotranspiration method proposed by Hargreaves and Samani (1985).

Traits evaluated

The saffron plants were harvested from pots 113 days after initial sowing. Plants were extracted with the root mass attached; root systems were then washed with water immediately after removal to preserve the root system. Root length was measured at the main root of a plant using a graduated ruler. Roots were subsequently dried in an oven at 60 °C for a period of 48 h and the weight of the root system of each plant was recorded.

Soil compaction under field conditions

Study site description

The field component of the study was conducted at the Cascavel-PR campus of the Western Paraná State University in an outdoor area adjacent to the greenhouse used in the controlled component of the study, from May to September 2018. According to the Köppen classification, the climate of the site is of a subtropical Cfa type, without a defined dry season; the hottest period averages temperatures higher than 22 °C with the coldest month averaging below 18 °C; with hot summers in winter and infrequent frosts. The meteorological variables for the experimental period are shown in Fig. 4.
The soil type used in the field experiment is classified as an Oxisol with a clayey to very clayey texture (600 g kg^{-1} of clay, 320 g kg^{-1} of silt and 80 g kg^{-1} of sand) (Embrapa, 1997), soft undulating relief, and basalt substrate (Embrapa, 2018). For the control component of the study, before starting the experiment, the chemical characteristics of the soil were determined (0–0.2 m; Table 3) according to the methods of Embrapa et al. (2009).

Treatments and experimental design

The experiment was conducted in an area of field, with four compaction levels (treatments) established by the number of passes (0, 1, 3, and 5 passes) of a farm tractor (New Holland 7630 (76 kW)), with a full 700-liter sprayer (Corisco 700) attached (total weight of $\cong$ 7.1 t). The field used for the four treatments comprised an area of 5 × 3 m, in which two rows of safflower seeds were sown with 0.6 m spacing between rows. Field planting was performed in March 2018; 33 seeds were sown per meter.

Traits evaluated

The harvest was performed 110 days after initial sowing. Using the same methods as for the controlled experiment, plants were extracted, together with the root mass, and were washed with water to preserve the entire extension of the root system. Root length was measured at the main root using a graduated ruler. The roots were then dried in an oven at 60 °C for a 48-hour period and their dry weight was recorded. Plant shoots were also dried in an oven at 60 °C but for an extended period of 72 hours.
After harvesting of safflower plants, soil samples were collected for soil physical characterization, in which the; bulk density, total porosity, microporosity, and macroporosity of the soil were determined. Samples were collected from opened trenches for each experimental plot and undisturbed samples were collected using volumetric stainless-steel rings with a volume of approximately 98 cm³ (0.5 m in diameter and 0.5 m in height) from three soil layers (0–0.1, 0.1–0.2, and 0.2–0.3 m), with the aid of a soil hammer and a soil extractor. The procedures for calculating these physical attributes followed the methodology recommended by Embrapa (1997).

Statistical analyses

Data were analyzed using analysis of variance (ANOVA). For experiments under controlled conditions, regression analysis was performed (significance level = 0.05). For experiments in field conditions, a Tukey test was performed (significance level = 0.05). Statistical analyses were conducted with SISVAR version 5.6.

Conclusions

Safflower root growth decreased when soil compaction increased ranging from 1.1 to 1.5 Mg m^{-3} under controlled (greenhouse) conditions. In field conditions, we observed a reduction in root length, root dry matter, and fresh and dry matter in roots and shoots of safflower as the soil compaction increased to 5P (1.28 Mg m^{-3}). Soil compaction in no-tillage is important under subtropical conditions due to the severe rates of decomposition of crop residues. In this sense, safflower has been shown to have some sensitivity to soil compaction.

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