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SOIL AND PLANT NUTRITION - Article

Safflower root and shoot growth affected by soil compaction

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ABSTRACT: Safflower (*Carthamus tinctorius L.*) is a commercial seed crop grown for its good yield of high-quality oil. It is tolerant to water stress but may be sensitive to soil compaction. The aim of this study was to assess safflower growth under different degrees of soil compaction at depths of 0.15 m to 0.20 m. The experiment was carried out in PVC pots constructed from three rings. Five levels of penetration resistance (0.20, 0.33, 0.50, 0.93, and 1.77 MPa) were applied in the intermediate ring, and two safflower genotypes, IMA-4904 and IMA-2106, were examined. There was no difference between safflower genotypes with respect to their resistance to soil compaction, which reduced root length density in the compacted layer and changed the root distribution in the soil profile, but did not prevent the roots from crossing the compacted layer and developing in depth. Increased soil bulk density in the compacted layer increased root diameter of the IMA-2106 genotype. Penetration resistance levels over 0.20 MPa (density of 1.2 mg·dm^{-3}) limited safflower root development. The maximum safflower growth occurred when the soil penetration resistance was 0.86 MPa. In this study, the Q1/2 index was higher than 1.77 and 1.55 for the IMA-2106 and IMA-4904 genotypes, respectively. Hence, safflower has proven to be tolerant to soil compaction, and stands out as a species with potential to decrease soil bulk density.

Key words: *Carthamus tinctorius* L., root length, bulk density, penetration resistance.

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INTRODUCTION

Given the need for the introduction of plants with industrial potential that are also tolerant to abiotic stresses characteristic of tropical climates, Safflower (*Carthamus tinctorius* L.) is a species that can be grown as a fall-winter crop in some regions of Brazil. It is an oilseed crop with great potential for cultivation in dry areas (Lovelli et al. 2007; Santos et al. 2017), producing seeds with a considerable content of high quality oil (35% – 45%), which may be used for human consumption and industrial use. Safflower oil has high levels of oleic (30%) and linoleic acids (70%), and it may also be used as a raw material for biodiesel production (Ilkılıç et al. 2011).

The ability of plants to obtain water and nutrients from soil is related to extensive root growth. Compacted layers increase soil resistance to penetration of roots, restricting growth at greater soil depth and therefore hindering access to groundwater (Ishaq et al. 2001). However, species differ in their ability to overcome layers of compacted soils (Rose et al. 2009), depending on the size of soil pores and root diameter (Clark et al. 2003).

Soil compaction is considered to be one of the main causes of soil degradation (Roque et al. 2010). It occurs mainly due to the heavy use of agricultural machinery and equipment (Lima et al. 2013) and seriously limits plant development. Excessive compression can reduce the absorption of nutrients by plants as well as the infiltration and redistribution of water in the soil (Chen et al. 2014; Nosalewicz and Lipiec 2014). Due to root growth restriction, morphological changes such as increased diameter and formation of twisted roots (Silva and Rosolem 2001) may occur depending on the species or cultivar used (Materechera et al. 1992). The penetration resistance level of 2.0 MPa is considered critical for the growth of most plants (Moraes et al. 2014).

According to Feizi et al. (2010), safflower has a deep root system, which can enable higher tolerance when subjected to water stress. Safflower is still little known in Brazil and studies on its management are scarce, particularly on its development in compacted soil conditions. Thus, considering safflower's rusticity and with the hypothesis that it may have growth potential in compacted soils, this study was designed to assess the development of safflower shoots and roots in an Oxisol subjected to five levels of compression.

MATERIALS AND METHODS

Location and climatic conditions

The experiment was carried out in a greenhouse at Botucatu College of Agricultural Sciences, São Paulo State University, in November 2015. The soil was collected from a depth of 0.00 – 0.20 m in a Rhodic Acrudox (Soil Survey Staff 2010), Dystroferric Red Latosol in Brazil (Embrapa 2013), and was sieved through a 4-mm mesh. The chemical analysis based on the recommendations of Raij and Quaggio (1983) indicated pH 5.1 in $CaCl_2$ (0.01 $mol{\cdot}L^{-1}$); 27 $g{\cdot}dm^{-3}$ organic matter; 34 $mg{\cdot}dm^{-3}$ P (Resin-P); 7 $mmol_c{\cdot}dm^{-3}$ of K^+; 48 $mmol_c{\cdot}dm^{-3}$ of Ca^{2+}; 17 $mmol_c{\cdot}dm^{-3}$ of Mg^{2+}; 105 $mmol_c{\cdot}dm^{-3}$ of cation exchange capacity (CEC); and 68% saturation basis. The soil comprised 630 $g{\cdot}kg^{-1}$ sand, 90 $mg{\cdot}kg^{-1}$ silt, and 280 $g{\cdot}kg^{-1}$ clay (Embrapa 2011). The maximum soil water retention capacity, assessed in a tension table at 0,03 MPa, was 180 $g{\cdot}kg^{-1}$.

Treatments and experimental design

The pots were assembled using overlapping PVC rings with an internal diameter of 0.10 m. The height of the top and bottom rings of the pots was 0.15 m, and the height of the intermediate ring, in which we placed the soils of different compaction levels, was 0.05 m. The rings were joined with plastic tape and we placed a 2-mm screen in the bottom. On the intermediate ring, we folded the edge of the tape into the pot to create an obstacle to avoid preferential growth along the walls. To prepare the rings of the compacted layer, the mass required to fill the PVC ring was calculated, and then compaction of the soil was carried out by applying light pressure with an iron cylinder measuring the same internal diameter as the rings.

The penetration resistance levels (Figure 1) were determined based on density values of 1.2, 1.3, 1.4, 1.5, and 1.6 $Mg{\cdot}m^{-3}$ using a bench penetrometer (Marconi Model MA 933) with a 4-mm diameter shank and 6-mm diameter conical tip, a semi-angle of 30°, and a base area of 0.126 cm^2. The speed of vertical displacement of the shaft was 1.0 $cm{\cdot}min^{-1}$, to a depth of 4.0 cm, to ensure that a layer of 3.5 cm had been crossed.

Fertilizer was applied as follows: 100 $mg{\cdot}dm^{-3}$ P (single superphosphate), 120 $mg{\cdot}dm^{-3}$ K (as potassium chloride), and 100 $mg{\cdot}dm^{-3}$ N (as urea) mixed with the entire volume of soil. After assembling the pots, we sowed the safflower seeds →

(IMA-2106 and IMA-4904), leaving two seedlings per pot five days after emergence. We monitored soil moisture daily by maintaining it close to field capacity by means of weighing and water application on the surface and in the subsurface. The total mass of pots with a water content of 80% of field capacity was determined and maintained throughout the experiment by daily weighing and by replacing the water through surface application according to the methodology of Rosolem et al. (2002). At 25 days after emergence, we dismantled the pots and collected the roots from each layer (top, compacted and bottom).

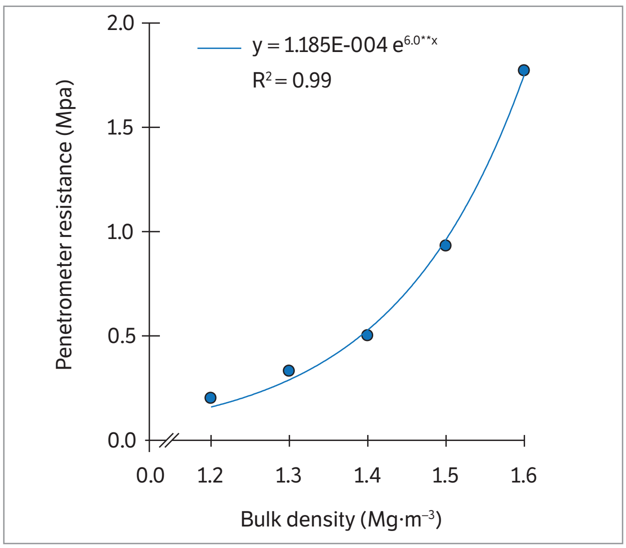

Figure 1. Penetrometer resistance in the compacted layer (0.15 m – 0.20 m) as affected by soil bulk density. ** significant at 1%.

Traits evaluated

The images of the roots were scanned in an optical reading scanner with a resolution of 300 dpi and analyzed on the program WinRhizo version 3.8-b (Regent Instrument Inc., Quebec, Canada). The density of root length and average root diameter were assessed. In the compacted soil layer, the Q1/2 index was determined using the adjusted model for root length density of the compacted layer (Dexter 1987). This index is the value of mechanical soil resistance to penetration in which the root growth is reduced by 50%. Which is the amount of mechanical soil resistance to penetration, measured with a penetrometer, in which the root growth is reduced to half of the maximum. Subsequently, we dried the roots in an oven at 60 °C for 48 h and determined their individual weight (total dry matter). We also dried the plant shoots in an oven at 60 °C for 72 h.

Experimental design and Statistical analyses

The experimental design consisted of randomized blocks with five different soil compaction levels and four replications, in a 2 × 5 factorial scheme. Data were subjected to regression analysis at 5% ($p \leq 0.05$) according to the *F*-test and the genotypes compared using the *t* test (LSD) at 5%. Regression analysis was performed in Sigma Plot 11.0 software (Jandel Scientific, Sausalito, CA, USA).

RESULTS AND DISCUSSION

The penetration resistance level in the compacted layer varied between 0.20 and 1.77 MPa (Figure 1) in the 0.15 m to 0.20 m deep. These values are close to those reported by Foloni et al. (2006) in a clay-textured Red Nitosol (0.26 to 1.98 MPa), and Falkoski Filho et al. (2013) in a dystrophic Red Nitosol (0.41 to 1.92 MPa), which are soils with similar textures.

The dry matter production of safflower shoots (Figure 2a) increased when the penetration resistance level was increased to 0.79 and 0.93 MPa for the IMA-2106 and IMA-4904 genotypes, respectively. Similar behavior has been reported in other crops including vetch, stubble turnips, black oat, white oat (0.10 to 1.34 MPa) (Müller et al. 2001), a *Stylosanthes* cultivar (1.0 to 1.83 Mg·m^{-3}) (Castagnara et al. 2013), cotton (0.41 to 1.92 MPa) (Falkoski Filho et al. 2013), pearl millet (1.28 to 1.74 Mg·m^{-3}) (Guimarães et al. 2013), and cover crops (1.10 to 1.90 Mg·m^{-3}) (Lima et al. 2015). This is due to the fact that at low penetration resistance levels, with very loose soil, the contact between soil and root is deficient, so a small increase in pressure results in better conditions for absorbing water and nutrients without hindering growth (Müller et al. 2001). The decreases observed in the dry matter of shoot accumulation from the penetration resistance studied (0.79 and 0.93 MPa) are 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), similar to the present study.

Root dry matter (Figure 2b) decreased at the first compression treatment for both genotypes as penetration resistance levels were increased (0.20 to 1.77 MPa). According to Materechera et al. (1992), with increased penetration resistance levels, the roots undergo morphological and physiological changes that are specific for each species

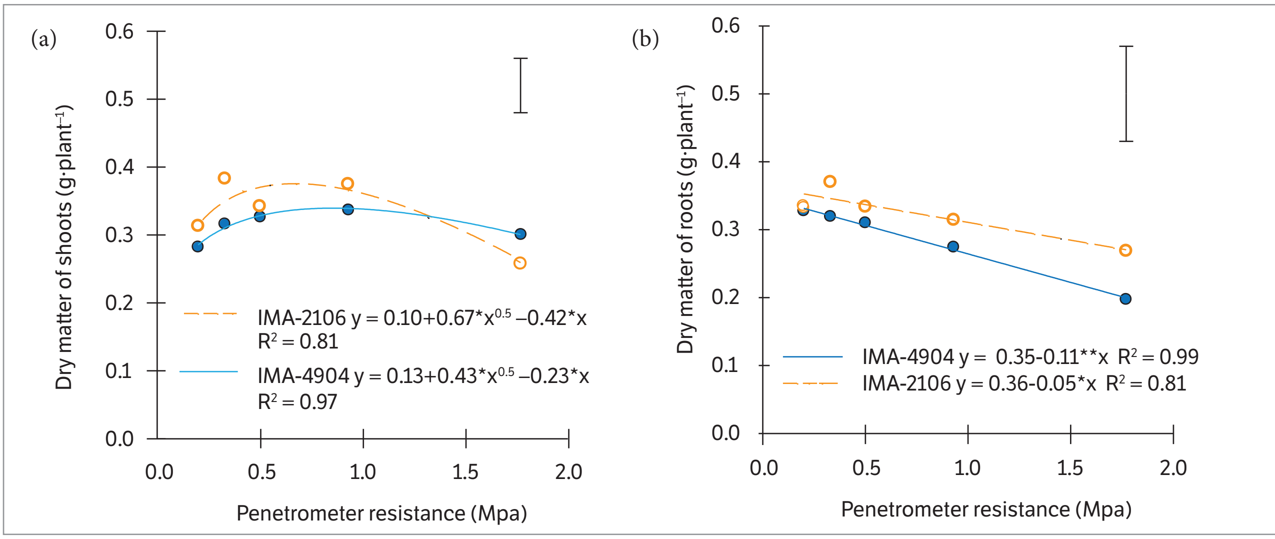

Figure 2. Dry matter of shoot (a) and full root (b) as affected by penetrometer resistance. ** significant at 1%; * significant at 5%. Vertical bars indicate least significant difference by t test (LSD) at 5% probability.

or genotype in order to adapt. Other studies also show results of root dry matter affected by soil compaction due to genotypes or cultivars, for example, maize in a medium texture Distroferric Red Latosol (1.28 to 1.68 $Mg{\cdot}m^{-3}$) (Foloni et al. 2003), and soybean in a clay-textured Red Nitosol (0.26 to 1.98 MPa) (Foloni et al. 2006).

Despite soil compaction having significant effects on root and shoot dry matter production by modifying the root distribution throughout the soil profile in both genotypes, only the IMA-2106 genotype showed a reduction in the total root length density influenced by the penetration resistance level (Figure 3). It differed from the IMA-4904 genotype by only 0.33 MPa.

In this study, according to the adjusted equations (Figure 2b), the value of Q1/2 was higher than 1.77 and 1.55 for the IMA-2106 and IMA-4904 genotypes, respectively. With the exception of the penetration resistance level of 1.77 MPa, the IMA-4904 genotype was the most sensitive. However, we observed Q1/2 values higher than those found for *Glycine max* – 1.22 MPa, *Dolichos lablab* – 1.46 MPa (Foloni et al. 2006), *Pennisetum glaucum* – 0 73 MPa, *Sorghum bicolor* – 0.30 MPa –, *Crotalaria juncea* – 0.97 MPa, and *Helianthus annuus* – 0.86 MPa (Rosolem et al. 2002). Thus, safflower has proven to be more tolerant to soil compaction than these species, and to stand out as a plant with the potential to decrease soil bulk density.

Merrill et al. (2002), in a study on the root length of eight species, found that safflower had the highest root length density. Thus, the characterization of soil mechanical impedance, in which 50% of root growth is impaired (Q1/2 index), is a way of measuring species sensitivity to compaction. However, the number of roots that penetrate a certain volume of compacted soil defines the potential of the plant to form “biopores” and improve soil physical conditions for the subsequent crop (Foloni et al. 2006).

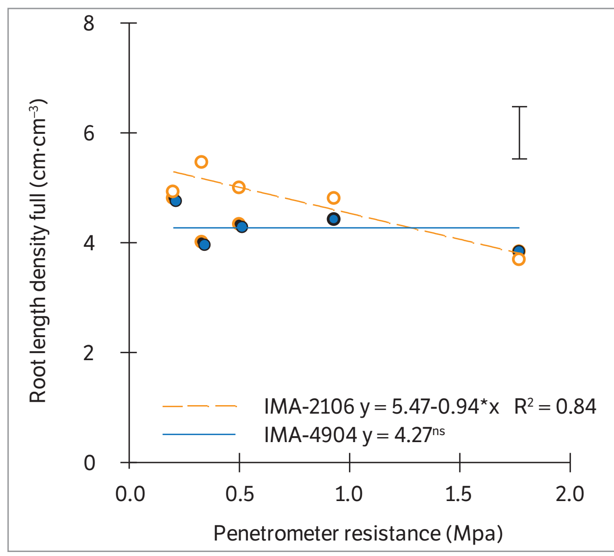

Figure 3. Root length density full as affected by penetrometer resistance. ns: not significant; * significant at 5%. Vertical bars indicate least significant difference by t test (LSD) at 5% probability.

Increased soil density in the compacted layer did not influence root length density in the top layer (Figure 4a). It did not confine the roots on the soil surface, which is a common behavior in plants that are sensitive to soil compaction (Silva et al. 2014). Similarly, the compressed layer did not restrict root length density (Figure 4c), indicating that safflower seedlings could explore and colonize deep into the ground and import nutrients even in adverse conditions after exceeding the physical impedance. This explains the crop's hardiness, as an oilseed plant with a deep root system and tolerance to drought will be able to overcome abiotic stresses (Merrill et al. 2002).

Safflower root diameter in the top and bottom layers (Figure 5a, c) was not affected. In the compacted layer (Figure 5b), the root diameter of the IMA-2106 genotype

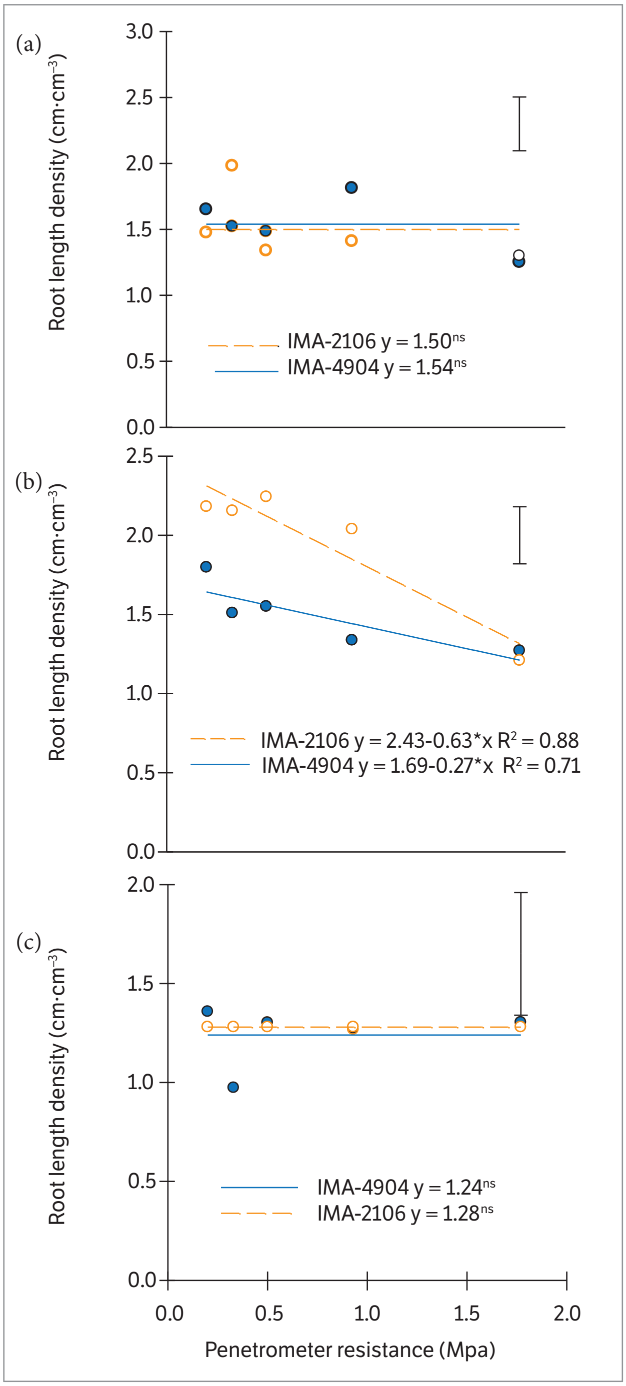

Figure 4. Root length density in (a) the upper layer, (b) compacted soil layer and (c) below the compacted layer as affected by penetrometer resistance. ns: not significant; * significant at 5%. Vertical bars indicate least significant difference by t test (LSD) at 5% probability.

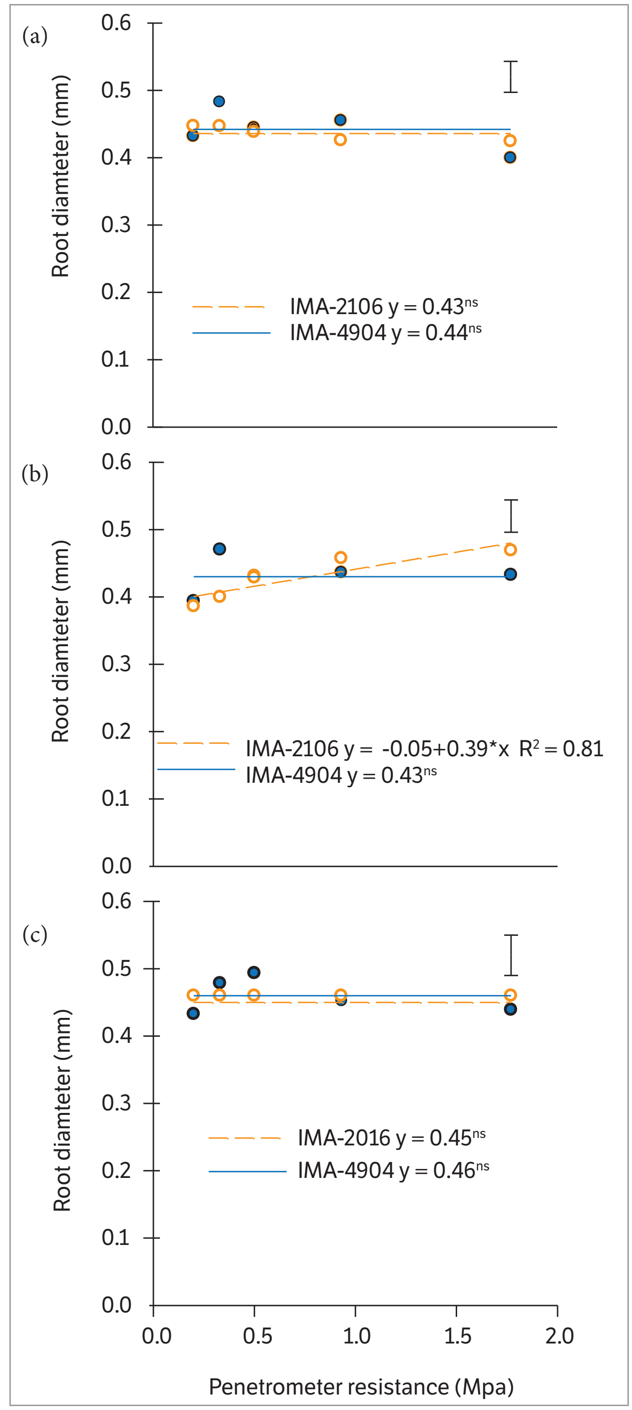

Figure 5. Root diameter in (a) the upper layer, (b) compacted soil layer and (c) below the compacted layer as affected by penetrometer resistance. ns: not significant; * significant at 5%.

increased with increased mechanical resistance to penetration, which corroborates the results found in the literature (Foloni et al. 2003; Foloni et al. 2006). The penetration resistance levels did not modify the root diameter of the IMA-4904 genotype. Scapinelli et al. (2016) observed a 20.2% increase in the diameter of sunflower roots with increased penetration resistance (0.90 to 2.04 MPa) in a layer of 5 cm to 10 cm deep. In compacted soils, there is a lack of oxygen, causing hypoxia, which results in higher ethylene production in roots. This hormone is associated with the inhibition of elongation and induction of swelling of the roots (Geisler-Lee et al. 2010), resulting in an increase in root diameter.

CONCLUSION

There was no difference between safflower genotypes regarding their resistance to soil compaction, which reduced root length density in the compacted layer, changed its distribution in the soil profile, but did not prevent the roots from crossing this layer and developing in depth. Increased soil bulk density in the compacted layer increased the root diameter of the IMA-2106 genotype. Penetration resistance levels above 0.20 MPa (density of 1.2 mg·dm^{-3}) limited safflower root development. Maximum safflower growth occurred when the soil penetration resistance was 0.86 MPa. In this study, the Q1/2 index was higher than 1.77 and 1.55 for the IMA-2106 and IMA-4904 genotypes, respectively. Hence, safflower has proven to be tolerant to soil compaction, and to stand out as a species with potential for decreasing soil bulk density.

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