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ORIGINAL PAPER

Physical properties of soil in *Pine elliottii* and *Eucalyptus cloeziana* plantations in the Vhembe biosphere, Limpopo Province of South Africa

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Abstract Plantation establishment using invasive alien plants is common in South Africa, but the effects of these plants on soil physical properties in the Vhembe biosphere is unknown. In this comparative study, soils underneath *Pinus elliottii* and *Eucalyptus cloeziana* were assessed for differences in physical properties compared to soils underneath adjacent natural sites in the Entabeni plantation in the Vhembe biosphere in Limpopo Province, South Africa. Soils were collected from topsoil over 3 months and quantified for gravimetric soil moisture, penetration resistance, soil infiltration, hydraulic conductivity and soil water repellency. For all 3 months, soils from both *P. elliottii* and *E. cloeziana* plantations were compact and had low penetration resistance compared to soils from adjacent natural sites. Soil infiltration and hydraulic conductivity were significantly ($p < 0.05$) lower in soils from plantations compared to soils from adjacent natural sites, and more so from the *E. cloeziana* plantation than from *P. elliottii*. Soil water repellency was observed in soils from *E. cloeziana* only in May and June. Soils from the invasive alien tree plantation have decreased soil moisture, infiltration rate, hydraulic conductivity and are compact as well as repellent (only *E. cloeziana*), all poor soil physical properties. However, this decline in soil physical properties was not uniform between the two invasive alien plantation species; hence we cannot generalize about the effects of invasive alien plantation species on soil physical properties, and further research is required across different ecological regions.

Keywords Litter · Biomass · Hydrophobicity · Invasive alien trees · Soil water repellency

Introduction

Plantation forests contribute billions of rands to the economy of South Africa and employ thousands of people (Brundu and Richardson 2016). Downstream industries that benefit from plantation forestry produce timber products that are exported, thus earning South Africa foreign currency. Besides monetary benefits, plantation forests provide multiple products and ecosystem services that support biodiversity and human livelihoods (Brockerhoff et al. 2008; Brundu and Richardson 2016). However, the establishment of plantation forests has come with a huge cost to the country's natural capital (Brundu and Richardson 2016). The negative impacts caused by invasive alien plantation trees include surface runoff and reduced stream flow (Van Lill et al. 1980; Le Maitre et al. 1997; Scott et al. 1998), and losses to ecosystem functioning and biodiversity (Van Wilgen and Richardson 2012; Brundu and Richardson 2016).

Despite the extensive body of literature on the effects of invasive alien plantation trees on soil properties (Titshall

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et al. 2013), few studies have looked at soil physical properties such as infiltration and water repellency. On the basis of previous studies in South Africa on the effects of invasive alien plantation trees on soils after short rotation plantations (Rietz 2010), post plantation harvesting (Grey and Jacobs 1987; Ross et al. 2005), and site-specific management options (du Toit et al. 2010), changes in soil properties in invasive alien tree plantations seem to be influenced by several complex and interacting factors, e.g., the tree species, plantation management, soil type, and climate. Other studies have shown that plantation trees alter soil properties (e.g., soil organic matter, nutrients, topsoil structure and compaction) through litter production (Turner and Lambert 1988; Li et al. 2006; Demessie et al. 2012; Wang and Xin 2016), while others attribute changes in soil properties to plantation management (Titshall et al. 2013). Studies on water infiltration, water runoff, soil water repellency and sedimentation in plantations have provided mixed results. Eldridge and Freudenberger (2005) showed that water infiltrates faster underneath plantation trees than in agricultural soils. Rodríguez-Alleres and Benito (2011) showed spatial and temporal variations in soil water repellency in pine and eucalyptus tree plantation trees, and these variations were driven by seasonal changes. Smith (2006) and Rietz (2010) concluded that mechanization in invasive alien tree plantations increases soil bulk density, which subsequently affects soil strength and compaction. Generally, invasive alien tree plantation have varied effects on soil properties that could be site or region specific; hence the generality of these observations needs to be assessed across a variety of sites and regions.

Both pine and eucalypt species are commonly used in South Africa's plantation forests, yet they are listed among the "100 world's worst invaders" (Lowe et al. 2000). Since their introduction in South Africa from the northern hemisphere, pines have been cultivated for decades (Price et al. 1998; Moran et al. 2000). To date, about 16 pine species are regarded as invasive, with the most problematic being *P. pinaster*, *P. radiata*, and *P. patula* which have displaced native plants and reduced water run-off in river catchments (Moran et al. 2000). The *Eucalyptus* species is endemic to Australia, and early introductions in South Africa were for forest plantation purposes in the Cape Colony (Forsyth et al. 2004). To date, approximately 149 *Eucalyptus* species have become established in the country (Forsyth et al. 2004), with most being found in plantations and along rivers (Van Lill et al. 1980).

The main aim for this study was to assess whether soils in plantations of *P. elliottii* and *E. cloeziana* have different physical properties compared to soils in adjacent natural sites at Entabeni plantations in the Vhembe biosphere which is located in Limpopo Province, South Africa. We specifically analyzed gravimetric soil moisture, penetration resistance levels, soil infiltration, hydraulic conductivity and soil water repellency.

Materials and methods

Study sites and experimental design

Soils were collected from *P. elliottii* and *E. cloeziana* sites located in Entabeni plantations (23°03′01.89″S; 30°13′22.77″E) between Thohoyandou and Louis Trichardt in Limpopo province, South Africa (Fig. 1). *P. elliottii* and *E. cloeziana* sites were selected because they have mature plantation tree and were adjacent to natural sites with approximately the same density (Table 1) and canopy cover ($> 70\%$). The *P. elliottii* stand was planted in 1999 with a density of 816 stems per hectare and later thinned to 666 stems per hectare in 2010. The *E. cloeziana* stand was planted in 2009 with a density of 816 stems per hectare and thinned to 728 stems per hectare in 2013 (D. Liebenberg 2018, personal communication). The distance between the plantation and natural sites was less than 50 m, and an attempt was made to select sites with similar slope angle. Vegetation in the area is classified as Soutpansberg Mountain Bushveld (Mucina and Rutherford 2006), which falls in the savanna biome. Mean annual precipitation in the area is approximately 1050 mm, and most rain falls in summer between the month of October and April (Mucina and Rutherford 2006). The summer months are warm (16–40 °C, and the winter months are mild (12–22 °C). Soils in the study sites are highly weathered, acidic, shallow, red dystrophic and of low fertility with high clay fraction (Louw et al. 1994). They are derived from basalt and quartzitic sandstone of the Soutpansberg Formation (Mucina and Rutherford 2006). Soutpansberg Mountain Bushveld is dominated by a dense tree layer and a poorly developed grass layer. Common plant species in the natural sites include *Berchemia zeyheri*, *Vachellia karoo*, *Dombeya rotundifolia*, *Grewia ocidentalis*, *Rhus pentheri*, and *Ziziphus mucronata* (Mucina and Rutherford 2006).

Within each plantation and adjacent natural site, a 20-m transect (parallel to the R 524 road) was established. The transect comprised five soil collecting points that were 5 m apart. Transects were used to avoid random collection of soil samples and collecting soils from the same point. At each collecting point, two soils cores (60 cm apart) were collected to measure gravimetric soil moisture and soil water repellency. Soil samples were collected at a depth of 10 cm with a 10 cm diameter soil corer after the hand removal of overlaying debris. After soil collection, gravimetric soil moisture and soil water repellency were measured in the laboratory at the University of Venda in Thohoyandou, South Africa. Soil penetration resistance

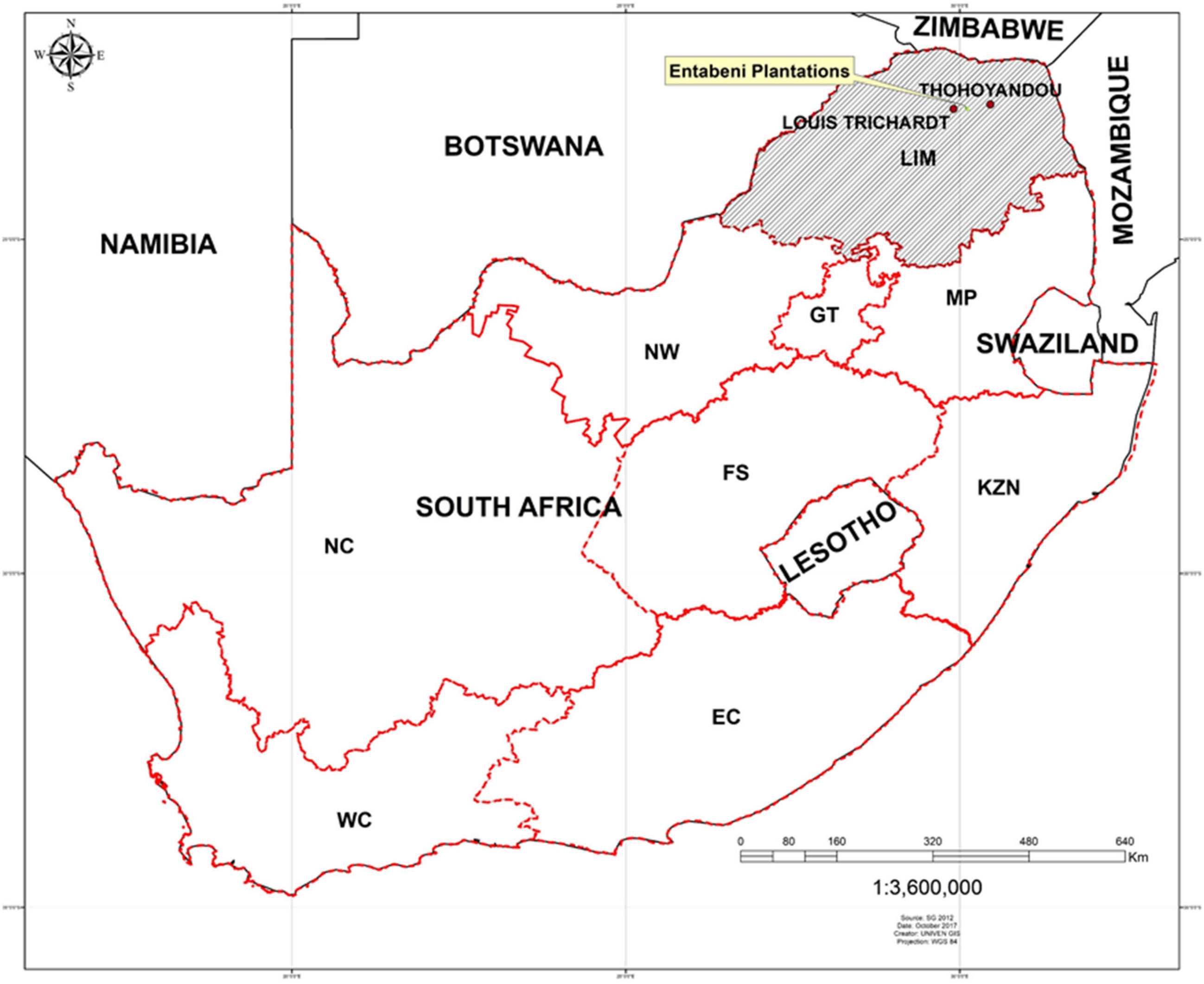

Fig. 1 Map showing the location of the study area in Limpopo Province (LIM) in South Africa

Table 1 Mean (± SE) plant height and diameter at breast height (DBH) of *P. elliottii* and *E. cloeziana* compared to trees from adjacent natural sites; *t* test results are shown

Variable	*P. elliottii site*	Natural site	*t* value	*E. cloeziana site*	Natural site	*t* value
Plant height (m)	45.00 ± 2.24	15.00 ± 2.24	9.45***	53.00 ± 3.39	20.00 ± 1.58	8.82***
DBH (cm)	120.00 ± 9.00	201.20 ± 49.26	1.62 ns	87.20 ± 5.63	118.40 ± 15.28	1.98 ns

and infiltration were measured at all collection points. All measurements were done monthly in April, May and June 2017. Twenty soil samples were collected per sampling month. Plant height for plantation trees and randomly selected native trees was visually estimated; diameter at breast height (DBH) was measured using a tape measure.

Soil measurements

Gravimetric soil moisture and penetration resistance

Soil moisture was measured in terms of gravimetric soil moisture which was expressed as a percentage. Soil cores were weighed wet, oven dried at 105 °C for 72 h and reweighed to obtain the water content (Black 1965). Soil penetration resistance, a measure of soil compaction, was measured by pushing a pocket penetrometer (Soiltest, Inc., Evanston, IL, USA) into the soil, allowing a metal ring to be pushed to scale and mark the penetration resistance value in kg cm^{-2} (Leung and Meyer 2003).

Soil infiltration and hydraulic conductivity

The infiltration rate and hydraulic conductivity in soils were measured with a mini disk infiltrometer (Decagon Devices, Pullman, WA, USA) after filling the upper and lower chambers of the infiltrometer with water. The top chamber controls the suction, which was calibrated at 2.0 cm. A small tube inside the infiltrometer, inserted a short distance above the porous sintered stainless steel disk regulates the suction rate (Latorre et al. 2013). The water in the lower chamber infiltrates the soil once the infiltrometer is placed on the soil, following litter removal. As water infiltrates, the level of water drops in the lower chamber, and the volume of water that infiltrated the soil was recorded every 30 s for 5 min. The infiltration rate was determined from the measured cumulative rate of infiltration over time (see Zhang 1997 for methods). Hydraulic conductivity was calculated from infiltration results using the van Genuchten–Zhang method (Zhang 1997, 1998). First, cumulative infiltration is measured over time and the results are fitted to Eq. (1) as:

$$I = C_1 t + C_2 t, \tag{1}$$

where I is the cumulative infiltration, t is time, C_1 and C_2 are parameters (C_1 is related to soil sorptivity and C_2 is related to hydraulic conductivity). The hydraulic conductivity of the soil (K) is then computed from Eq. (2) as:

$$K = C_2 A, \tag{2}$$

where C_2 is a parameter related to hydraulic conductivity and A is a value related to the van Genuchten parameters from a given soil type to the suction rate and radius of the infiltration disk (Fatehnia et al. 2014). For more information on the equations and method of calculating the hydraulic conductivity, see the mini disk infiltrometer manual by Decagon Devices (2014).

Soil water repellency

The water droplet penetration time (WDPT) method was used to measure soil water repellency in the laboratory (Doerr and Thomas 2000). The method measures how long repellency persists on a porous soil surface (Granged et al. 2011). Collected soil samples were first sieved through a 2-mm sieve. They were air-dried and kept under standard laboratory conditions at approximately 23 °C (± 2 °C) which is similar to average autumn temperatures in Thohoyandou. After drying for 7 days, soil samples were set in Petri dishes and leveled. Five drops of distilled water were applied to different locations on each sample using a hypodermic syringe. The time taken for the water to penetrate the soil was recorded, and the average penetration time for the five drops was recorded as the WDPT for each soil sample (Doerr and Thomas 2000; Ruwanza et al. 2013). In this study, soils were classified as wettable when the water drop infiltrated within 5 s, slightly water repellent (> 5–60 s), strongly water repellent (> 60–600 s), severely water repellent (> 600–3600 s) or extremely water repellent (> 3600 s) (Bisdom et al. 1993).

Data analyses

Data were analyzed using SPSS version 25 (IBM, Armonk, NY, USA) (IBM Corporation SPSS 2017). Proof of normality and homogeneity of variance were performed using Kolmogorov–Smirnov tests and Levene's test, respectively, and data were normally distributed. Plant height and diameter were compared between plantation and natural trees using a t test. Soil physical properties were compared between sites using repeated measures ANOVA since data were collected for 3 months on the same transect. Therefore, the repeated measures ANOVA comprised sites and months as factors for each measured soil physical property. When the ANOVAs showed significant differences, Tukey's honestly significant difference (HSD) unequal n test was used to determine differences between sites at $p < 0.05$. Soil water repellency classes were analyzed using the Chi squared test.

Results

Plant height was significantly ($p < 0.001$) higher in the *P. elliottii* and *E. cloeziana* sites compared to plants in adjacent natural sites (Table 1). The average height for *P. elliottii* trees was 45.00 ± 2.25 m and 53.00 ± 3.39 m for *E. cloeziana* trees compared to 15.00 ± 2.25 m and 20.00 ± 1.58 m, respectively, in adjacent natural sites. Plant diameter showed no significant ($p > 0.05$) differences between plantation trees and trees in adjacent natural sites (Table 1).

Gravimetric soil moisture and penetration resistance levels

Gravimetric soil moisture was significantly ($p < 0.05$) higher in soils from adjacent natural sites compared to soils collected from either plantation species (Table 2), except for *P. elliottii* in April which showed no significant ($p > 0.05$) differences (Fig. 2a, b). Monthly comparisons on gravimetric soil moisture showed significant

Table 2 Results of repeated measures ANOVA testing effects of sites and months on soil physical properties of soil samples taken from *P. elliottii* and *E. cloeziana*

Variable	Sites		Months		Sites and months	
	F	*P*	*F*	*P*	*F*	*P*
P. elliottii						
Gravimetric soil moisture content (%)	**11.86**	**0.026**	**44.82**	**< 0.001**	2.15	0.193
Soil penetration resistance (kg/cm^2)	**65.26**	**< 0.001**	**198.90**	**< 0.001**	2.86	0.066
Cumulative infiltration (cm)	6.14	0.068	2.49	0.172	1.21	0.338
Soil hydraulic conductivity (cm/s 10^{-4})	**8.91**	**0.041**	3.73	0.106	3.01	0.125
E. cloeziana						
Gravimetric soil moisture content (%)	**22.02**	**0.009**	**78.26**	**< 0.001**	0.03	0.942
Soil penetration resistance (kg/cm^2)	**60.24**	**< 0.001**	**57.06**	**< 0.001**	**26.36**	**< 0.001**
Cumulative infiltration (cm)	**23.14**	**0.009**	**11.90**	**0.005**	**4.62**	**0.053**
Soil hydraulic conductivity (cm/s 10^{-4})	**22.07**	**0.009**	**7.10**	**0.017**	3.44	0.100

Significant effects at $p < 0.05$ are highlighted in bold

($p < 0.001$) differences for both plantation species (Table 2). The result showed higher gravimetric soil moisture in April and May compared to June for soils collected from *P. elliottii* and *E. cloeziana* (Fig. 2a, b). In the repeated measures ANOVA, the interaction between sites and months on gravimetric soil moisture showed no significant ($p > 0.05$) differences for soils from both plantations (Table 2). When the two plantation species were compared alone, gravimetric soil moisture was significantly ($p < 0.05$) higher for soils from *P. elliottii* than for soils from *E. cloeziana* (Table 3). Similarly, monthly comparisons on gravimetric soil moisture for the two plantation species differed significantly ($p < 0.001$). However, interactions between sites and months on gravimetric soil moisture for the two plantation species alone showed no significant ($p > 0.05$) differences (Table 3).

Penetration resistance levels were significantly ($p < 0.001$) higher in soils collected from both *P. elliottii* and *E. cloeziana* compared to soils collected from adjacent natural sites (Fig. 2c, d). Similarly, monthly comparisons of penetration resistance levels showed significant ($p < 0.001$) differences for soils collected from both plantation trees (Table 2). The result showed higher penetration resistance levels in May and June compared to April for soils from both *P. elliottii* and *E. cloeziana* (Fig. 2c, d). In this repeated measures ANOVA, interactions between sites and months on penetration resistance levels showed no significant ($p > 0.05$) differences for soils collected underneath both *P. elliottii* and *E. cloeziana* (Table 2). Comparisons between the two plantation species alone showed significant ($p < 0.01$) differences in penetration resistance levels (Table 3). Penetration resistance levels were higher in soils from *P. elliottii* than soils from *E. cloeziana* in May and June only (Table 3). Similarly, monthly comparisons and interaction between sites and months on penetration resistance levels for the two plantation species showed significant ($p < 0.001$) differences (Table 3). Generally, penetration resistance levels increased from April to June for soils underneath both *P. elliottii* and *E. cloeziana*.

Soil infiltration and hydraulic conductivity

The average infiltration rate in soils from *P. elliottii* in April was 1.6 cm after 5 min compared to 6.0 cm in soils from adjacent natural sites. In May, the mean was 1.0 cm from *P. elliottii* compared to 1.8 cm from soils in adjacent natural sites. In June, the mean was 1.8 cm from *P. elliottii* compared to 6.6 cm in soils from adjacent natural sites (Fig. 3a, c, e). However, infiltration rate between soils from *P. elliottii* and from adjacent natural sites did not differ significantly ($p > 0.05$) (Table 2). Similarly, monthly comparisons and interaction between sites and months on infiltration rates showed no significant ($p > 0.05$) differences for *P. elliottii* (Table 2). Infiltration rate comparisons between soils from *E. cloeziana* and from adjacent natural sites differed significantly ($p < 0.01$) (Table 2); infiltration rates in soils underneath adjacent natural sites were higher than in soils from *E. cloeziana* site (Fig. 3b, d, f). Monthly comparisons of infiltration rates showed significant ($p < 0.01$) differences for soils from *E. cloeziana*; infiltration rates were higher in April and May than in June (Fig. 3b, d, f). In this repeated measures ANOVA, interactions between sites and months on infiltration rates for soils underneath *E. cloeziana* showed significant ($p < 0.05$) differences (Table 2). Comparisons between the two plantation species alone showed no significant ($p > 0.05$) differences in infiltration rates (Table 3). Similarly, monthly comparisons and interaction between sites and months on infiltration rates for the two plantation species showed no significant ($p > 0.05$) differences (Table 3).

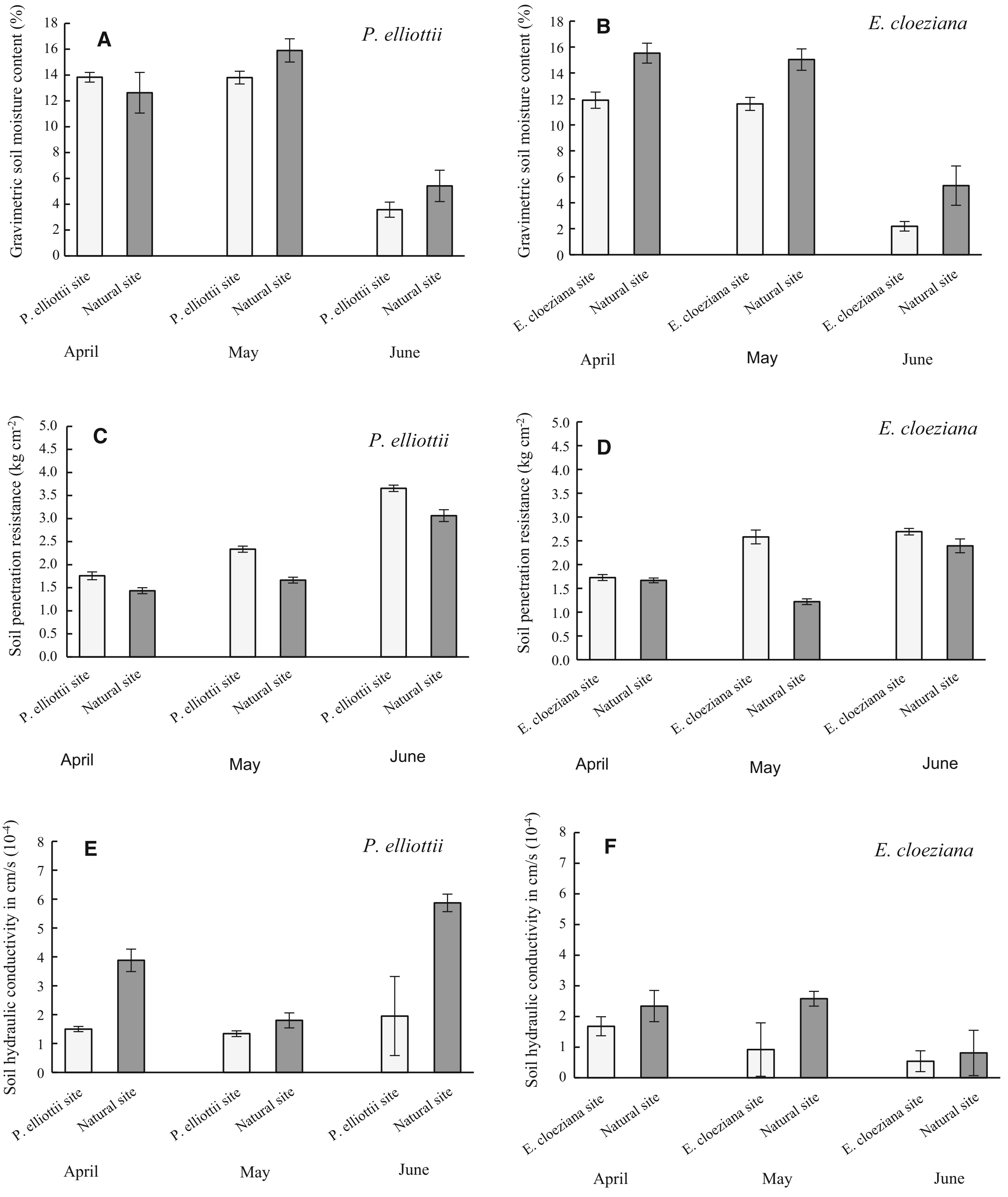

Fig. 2 Gravimetric soil moisture content (**a**, **b**), soil penetration resistance levels (**c**, **d**) and soil hydraulic conductivity levels (**e**, **f**) for *P. elliottii* and *E. cloeziana* in soil samples taken from plantation sites and adjacent natural sites over 3 months. Bars represent mean ± SE. Results of repeated measures ANOVA are shown in Table 2

Table 3 Soil physical properties (mean ± SE) of soil samples from *P. elliottii* and *E. cloeziana* sites

Variable	April		May		June		Repeated ANOVA (*F* and *P* values, measures within-subject effects)					
							Sites		Months		Sites and months	
	P. elliottii	*E. cloeziana*	*P. elliottii*	*E. cloeziana*	*P. elliottii*	*E. cloeziana*	*P*	*F*	*P*	*F*	*P*	*F*
Gravimetric soil moisture content (%)	13.83 ± 0.37	11.90 ± 0.63	13.80 ± 0.49	11.62 ± 0.50	3.58 ± 1.21	2.18 ± 0.37	**12.53**	**0.024**	**275.06**	**< 0.001**	1.27	0.330
Soil penetration resistance (kg/cm^2)	1.76 ± 0.08	1.73 ± 0.06	2.34 ± 0.07	2.58 ± 0.15	3.66 ± 0.07	2.39 ± 0.14	**10.18**	**0.002**	**188.13**	**< 0.001**	**28.42**	**< 0.001**
Cumulative infiltration (cm)	1.60 ± 0.51	1.60 ± 0.25	1.00 ± 0.01	0.80 ± 0.37	1.80 ± 0.80	0.40 ± 0.24	1.88	0.242	1.19	0.352	1.77	0.250
Soil hydraulic conductivity (cm/s 10^{-4})	1.50 ± 0.09	1.69 ± 0.31	1.34 ± 0.1	0.94 ± 0.87	1.95 ± 1.37	0.54 ± 0.74	2.35	0.200	0.82	0.455	2.61	0.169

Repeated measures ANOVA was used to test effects of sites and months on soil physical properties. Significant effects at $p < 0.05$ are highlighted in bold

Hydraulic conductivity was significantly ($p < 0.05$) higher in soils from natural sites than from *P. elliottii* or *E. cloeziana* sites (Table 2, Fig. 2e, f). Monthly comparisons on hydraulic conductivity showed significant ($p < 0.05$) differences for soils from *E. cloeziana* only (Table 2); hydraulic conductivity was higher in April and May than in June (Fig. 2f). In this repeated measures ANOVA, interactions between sites and months on hydraulic conductivity showed no significant ($p > 0.05$) differences for soils from both *P. elliottii* and *E. cloeziana* (Table 2). Comparisons between the two plantation species alone showed no significant differences in hydraulic conductivity (Table 3). Similarly, monthly comparisons and interaction between sites and months on hydraulic conductivity for the two planation species showed no significant ($p > 0.05$) differences (Table 3).

Soil water repellency

Water droplets infiltrated within 5 s in soils collected from *P. elliottii* and adjacent natural site for all 3 months, an indication that soils were wettable (Fig. 4). Differences in water repellency were only recorded in May and June in soils from *E. cloeziana*. The bulk of the soils from *E. cloeziana* in May were slightly repellent (60%), with the remaining soils strongly repellent (20%) or severely repellent (20%) (Fig. 4). Forty percent of the soils from *E. cloeziana* in June were wettable, with the remaining soils slightly repellent (40%) or severely repellent (20%). Chi squared analysis of WDPT classifications for May ($\chi^2 = 25.96$, $p = 0.0001$) and June ($\chi^2 = 29.15$, $p = 0.0001$) showed that water repellency differed significantly between soils from *E. cloeziana* and the adjacent natural site.

Discussion

The effect of the two plantation species on soil physical properties varied. Soils from both *P. elliottii* and *E. cloeziana* had low soil moisture and were compact compared to soils from adjacent natural sites. The results concur with previous studies that showed that soils underneath plantation trees have low soil moisture and are compact (Sands et al. 1979; Zhang et al. 2007; Zhao et al. 2015; Liu et al. 2017). However, other studies contradicted these results, showing no differences in soil moisture content between soils underneath *E. grandis* compared to soils from natural and cleared sites (Kerr and Ruwanza 2015). Also, Tererai et al. (2015) showed seasonal variations in soil moisture between soils from *E. camaldulensis* and natural areas. In this study, the reported low soil moisture levels from tree plantation compared to adjacent

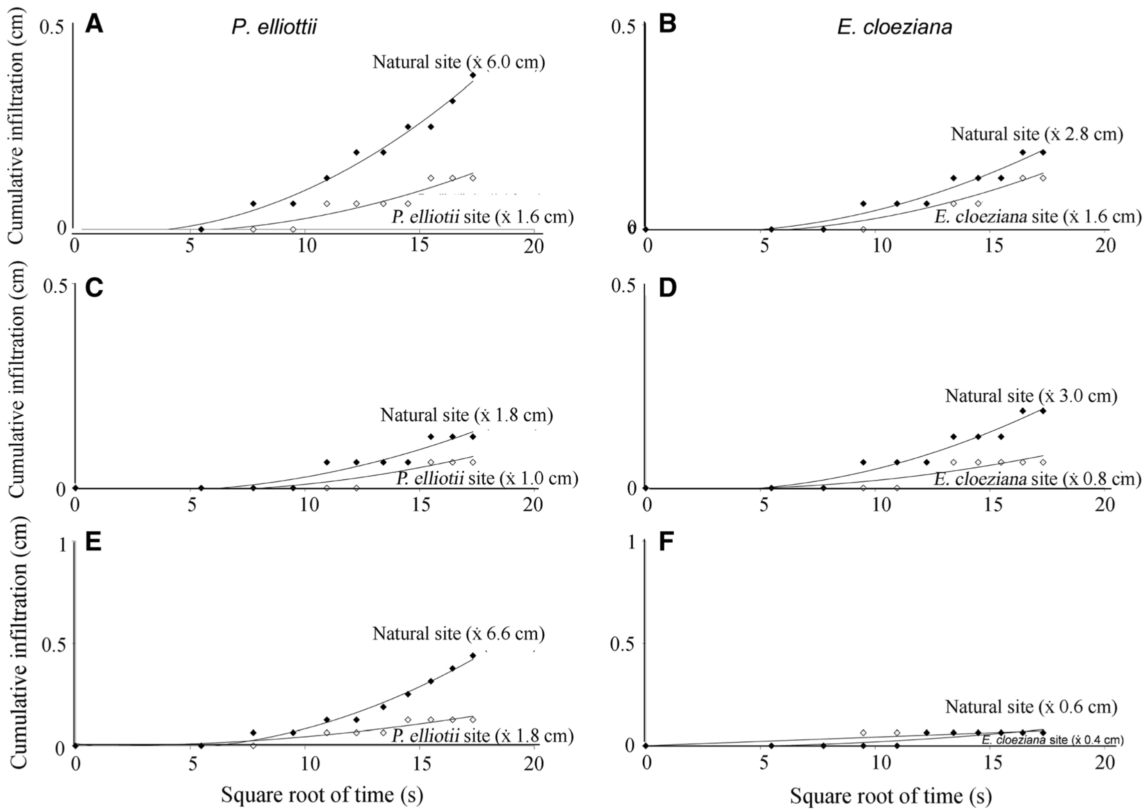

Fig. 3 Cumulative infiltration levels in soil samples taken from *P. elliottii*, *E. cloeziana* and adjacent natural sites for the months April (**a**, **b**), May (**c**, **d**) and June (**e**, **f**). Results of repeated measures ANOVA (based on average infiltration rate after 5 min) are shown in Table 2

natural sites could be a result of several factors. First, plantation trees (especially *Eucalyptus*) use high amounts of water, reducing soil moisture (Myers et al. 1996; Scott et al. 1998; Zhang et al. 2007; Zhao et al. 2015; Liu et al. 2017); this effect has been shown to increase with plantation age (Robinson et al. 2006; Liu et al. 2017). Second, evaporative water loss from soils and transpiration from plantation trees could also explain the low soil moisture content recorded from plantation soil compared to that from adjacent natural sites. Maier et al. (2017) confirmed that high evapotranspiration from plantation trees is linked to evaporative water loss from soils, thus making the soils dry and compact (Maier et al. 2017).

Our results on soil compaction concur with conclusions by Sands et al. (1979) who reported that soils from sites with native species were less compact than soils from adjacent pine plantations. Soil compaction is known to be dependent on soil moisture content, with moist soils being wettable and dry soils being compact, though this depends on the soil type (Jung et al. 2010). Besides changes in soil moisture being the possible driver of soil compaction, the release of allelopathic chemicals by some plantation trees (especially *Eucalyptus*) has been shown to trigger soil compaction (Espinosa-García et al. 2008). Also, compaction in soils in plantations has been linked to site management, particularly the harvesting method (Titshall et al. 2013). Mechanical harvesting of plantation trees can compact soil, which can persist even after the introduction of new trees (Smith 2006; Rietz et al. 2010).

Low infiltration and hydraulic conductivity rates were recorded in soils from *E. cloeziana* compared to adjacent natural sites, but not for *P. elliottii*. Our results on infiltration agree with results by Demessie et al. (2012) who reported low infiltration rates in *Eucalyptus* plantations compared to cultivated lands and native forest plantations in Ethiopia. Similarly, Madeira (1989) reported low infiltration rates and saturated hydraulic conductivity in *E. globulus* plantations in stands dominated by native species. These studies attributed the low infiltration rates in *Eucalyptus* plantations to changes in soil physical properties, which could be driven by factors such as tree type and disturbance. Indeed, changes in soil physical properties, e.g., high soil compaction, low soil moisture and reduced porosity can to cause low infiltration rates and hydraulic conductivity in plantation soils (Silva et al. 2008; Titshall et al. 2013). Several studies have reported that soil compaction reduces total soil porosity (Silva et al. 2008) and the number of macropores, thus causing low water infiltration and hydraulic conductivity (Madeira 1989; Hamza and Anderson 2005; Nawaz et al. 2013). On the other hand,

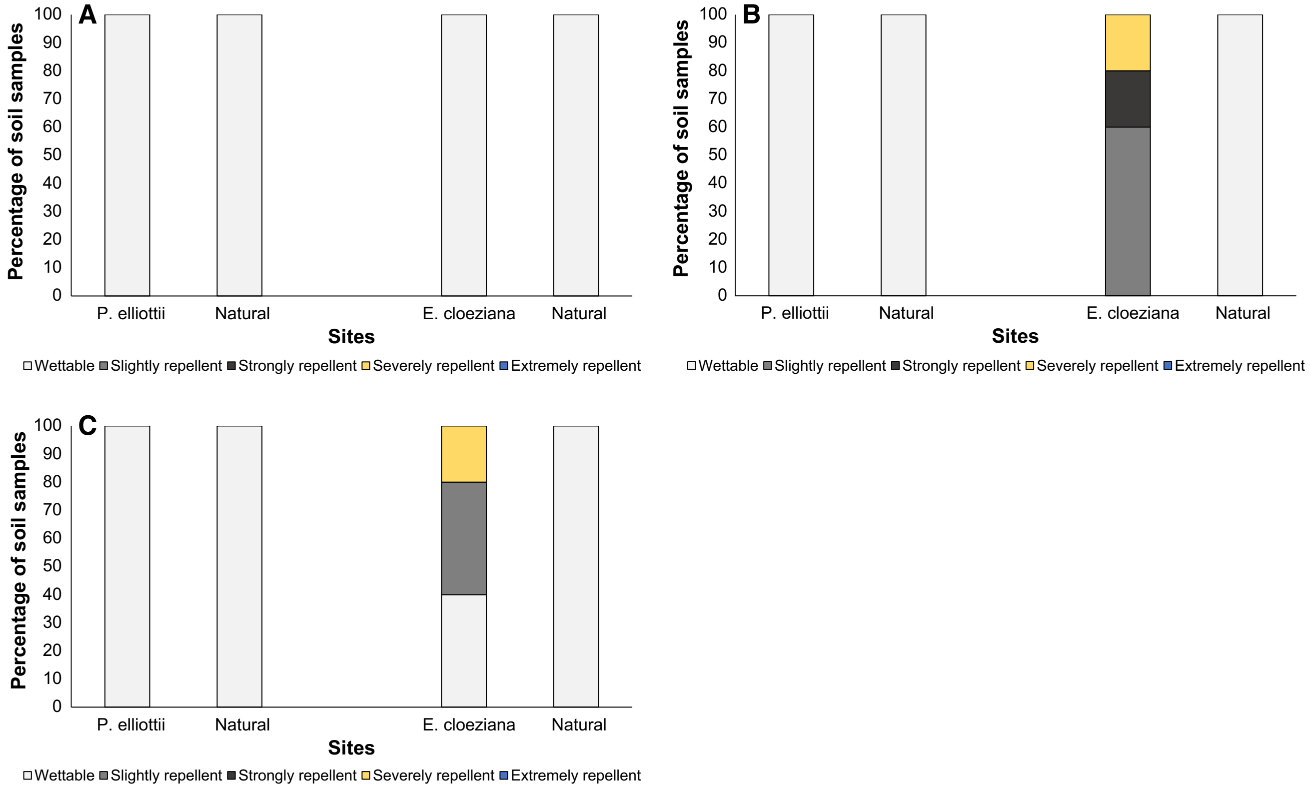

Fig. 4 Distribution of water repellency classes (WDPT) in soil samples from *P. elliottii*, *E. cloeziana* and adjacent natural sites in **a** April, **b** May, and **c** June

some studies have shown that repeated disturbances in plantations can cause changes in soil physical properties that lead to reduced infiltration (Ober and DeGroote 2014). For example, Pote et al. (2004) and Patterson et al. (2010) showed that consecutive litter rakings exacerbates physical changes in surface soil that cause a decrease in infiltration rate and porosity. Also, Smith (2006), Rietz (2010) and Titshall et al. (2013) reported that disturbances linked to mechanized harvesting of plantation trees can change soil physical properties (e.g., loss in soil porosity and soil strength), which then negatively affect infiltration and hydraulic conductivity.

Soils in the *P. elliottii* plantations and adjacent natural sites were all wettable for all three measured months. However, soil water repellency was higher for *E. cloeziana* in May and June. Our results concur with those of Santos et al. (2016) who showed that soil water repellency was more dynamic in eucalypt soil than in pine soil in Portugal. Several studies have shown that *E. camaldulensis* (Ruwanza et al. 2013) and *E. grandis* (Kerr and Ruwanza 2015) cause soil water repellency and reduce water infiltration. The release of allelopathic chemicals by *Eucalyptus* species has been identified as a cause of soil repellency (Ruwanza et al. 2013). The observed soil wettability in April in the *E. cloeziana* plantation compared to other months could be a result of seasonal variations. Seasonal variations in soil water repellency have been reported (Keizer et al. 2008; Santos et al. 2016), and these variations are a result of changes in environmental conditions especially rainfall patterns.

Conclusions

Results of this study are consistent with similar studies, showing a decline in soil physical properties from tree plantation compared to adjacent natural areas. However, the observed decline in soil physical properties is not uniform between the two plantations, likely as a function of plant type, plant water-use and human-mediated disturbances such as mechanical tree harvesting (Rietz et al. 2010; Titshall et al. 2013). This lack of uniformity highlights the need for caution in generalization about the impacts of invasive alien plantation trees on soil physical properties and the need to better understand the impacts of different invasive plantation species in different ecological regions.

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