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# Differential effects on soil water repellency of Eucalyptus and Pinus plantations replacing natural pastures

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**ABSTRACT:** Land-use changes from native pastures to forest plantations in humid temperate areas have raised concerns about their potential impact on the environment. This study aimed to assess the effects of such changes on soil water properties, focusing on the impact of the forest species planted and their relationship with changes in soil C content. Specifically, we aimed to identify the development of surficial soil hydrophobicity and changes in soil water holding capacity. A long-term forest experiment with variable planting densities (816, 1111, and 2066 trees $ha^{-1}$) of *Eucalyptus grandis* Hill ex Maiden and *Pinus taeda* L. was established in 2004 on native pasture vegetation. Undisturbed soil samples (0.00-0.03 m soil layer) were extracted from the experiment and surrounding pastures and soil water repellency was determined by the water drop penetration time (WDPT) method at three soil matric potential levels (SMP). Bootstrapping was used to test if the sample size was sufficient to obtain robust results. Replacing native pastures with forest plantations significantly increased surficial soil hydrophobicity, which was more pronounced under *Eucalyptus grandis* than under *Pinus taeda*. Soil water repellency increased with decreasing SMP, particularly in land-uses that generated higher initial hydrophobicity. Additionally, the soils under forest cover had less water retention capacity than those under pastures at each SMP, with larger differences when the soil was dried to more negative SMP. More research is necessary to determine if soil alterations from converting native pastures to forest plantations in temperate climates will lead to a significant decrease in soil water holding capacity and an increase in hydrophobicity at deeper depths.

**Keywords:** hydrophobicity, grassland, forest, forest management, afforestation, water holding capacity.

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## INTRODUCTION

Soil hydrophobicity, or water repellency, occurs when soils have a reduced affinity for water, resulting in delayed soil wetting for varying periods (Doerr and Thomas, 2000; Doerr et al., 2000). This is a widespread phenomenon (Ritsema and Dekker, 2000) observed in different climates, soils, and land-uses (Doerr et al., 2000; Jaramillo et al., 2000; Rodríguez-Alleres et al., 2007; Butzen et al., 2015; Vogelmann et al., 2017). Implications of soil water repellency are significant for both productivity and the environment, including available water reduction for plant growth due to decreased infiltration rates (Cerdà and Doerr, 2007), increased runoff and soil erodibility (Leighton-Boyce et al., 2007; Butzen et al., 2015), unstable wetting fronts and preferential flows (Ritsema et al., 1998; Dekker and Ritsema, 2000; Ritsema and Dekker, 2000), and the potential acceleration of pollutants leaching (Ritsema et al., 1998; Ritsema and Dekker, 2000).

Soil hydrophobicity is influenced by soil properties, with severity increasing as soil particle surface area decreases (Roper et al., 2015). Previous studies identified soil water content as a critical factor in characterizing soil hydrophobicity, as it can determine soil water repellency reduction in an initially hydrophobic soil, or even cause the phenomenon to disappear (Vogelmann et al., 2013, 2017; Kercheva et al., 2021). Specifically, Vogelmann et al. (2013) found that there is a moisture content above which the soil becomes hydrophilic. Although there are varying results regarding the dynamics of soil water repellency within the moisture content range between permanent wilting point and completely dry, all previous studies agree that hydrophobicity increases as soil moisture content decreases from saturation to the permanent wilting point (Fishkis et al., 2015). One possible explanation for this phenomenon is the reorientation of amphipathic substances during drying (Doerr et al., 2000; Mainwaring et al., 2013).

Several studies have reported positive correlations between soil organic carbon (SOC) content and surface soil water repellency (Zavala et al., 2009; Lozano et al., 2013; Mirbabaei et al., 2013; Mao et al., 2016). However, there are also studies in which no relationship was found between these variables (Teramura, 1980; Wallis et al., 1993). Therefore, it is suggested that soil hydrophobicity is not solely determined by the SOC content, but also by the type of organic compounds present in the soil (Doerr et al., 2000; Woche et al., 2005). Quantity and composition of SOC are strongly influenced by the vegetation cover, which is a key factor in the development of soil hydrophobicity by determining the presence of water-repellent organic compounds (Rodríguez-Alleres et al., 2007; Lozano et al., 2013). Perennial tree species, such as *Pinus* sp. and *Eucalyptus* sp., which produce significant amounts of resins, waxes, and aromatic oils, are known to induce soil water repellency (Doerr et al., 2000; Mataix-Solera et al., 2007; Rodríguez-Alleres et al., 2007; Verheijen and Cammeraat, 2007). In particular, *Eucalyptus* sp. has been reported to have a higher potential to induce soil hydrophobicity compared to *Pinus* spp. (Rodríguez-Alleres et al., 2007; Zavala et al., 2009). Organic matter distribution in forest soils causes hydrophobic organic substances to accumulate on the surface, developing the phenomenon mainly in the surficial mineral soil, enriched in organic matter (Rodríguez-Alleres et al., 2007; Benito et al., 2019). In contrast, carbon inputs from perennial herbaceous vegetation, such as native pastures, are less stratified (Sokol and Bradford, 2019; Villarino et al., 2021). Thus, land-use changes, such as the conversion from natural pastures to forest plantations, can alter the quantity, quality and distribution of SOC and consequently affect soil water repellency.

Río de la Plata grassland region (RPG) is the largest humid and subhumid grassland biome area in South America. Recent land-use changes in this region, as reported by Baeza et al. (2022), suggest that there could be an increase in the incidence and severity of soil water repellency. From 2001 to 2018, the natural pasture surface in the RPG decreased by 8-9 %, while the forest plantation surface increased by 100 % (Baeza et al., 2022).

Similar relative land-use changes have occurred within Uruguay, particularly in the RPG region (Baeza et al., 2022).

Soil water repellency evolution due to the establishment of forest plantations on natural grasslands in temperate climate zones has received little research attention despite its importance. Closing this knowledge gap is of particular relevance in the RPG region. Obtaining information from long-term experiments is critical to accurately assess the effects of land-use and management on soil properties (Hughes et al., 2017).

A long-term forest experiment was established to assess the impact of the land-use change from natural grasslands to *Pinus taeda* L. and *Eucalyptus grandis* Hill ex Maiden plantations at different planting densities on various soil properties. We hypothesize that the land-use change would increase mineral soil surface hydrophobicity, particularly under *Eucalyptus* sp. and at high planting densities. We also expect a positive association between soil water repellence and SOC content and a negative association with water content, with hydrophobic soils having lower water retention capacities. The general objective of this study was to determine the effect of replacing natural pasture vegetation with forest plantations on soil surface hydrophobicity persistence and water retention capacity, and its relationship with changes in SOC content. Specific objectives were to (i) assess the differential impact of forest species (*Pinus taeda* or *Eucalyptus grandis*) and planting density on soil properties and water repellency; and (ii) explore the relationship between soil water repellence and soil moisture retention dynamics.

## MATERIALS AND METHODS

### Site description

The study was conducted at Los Moros Farm (Route 5, km 451, Rivera Department, Uruguay, 31° 23' 55.11" S and 55° 41' 43.88" W) (Figure 1). A long-term forest experiment with variable planting densities of *Eucalyptus grandis* and *Pinus taeda* on native pasture vegetation was established in 2004. Thus, this site allows one to study the effects of three different vegetation covers on soil properties.

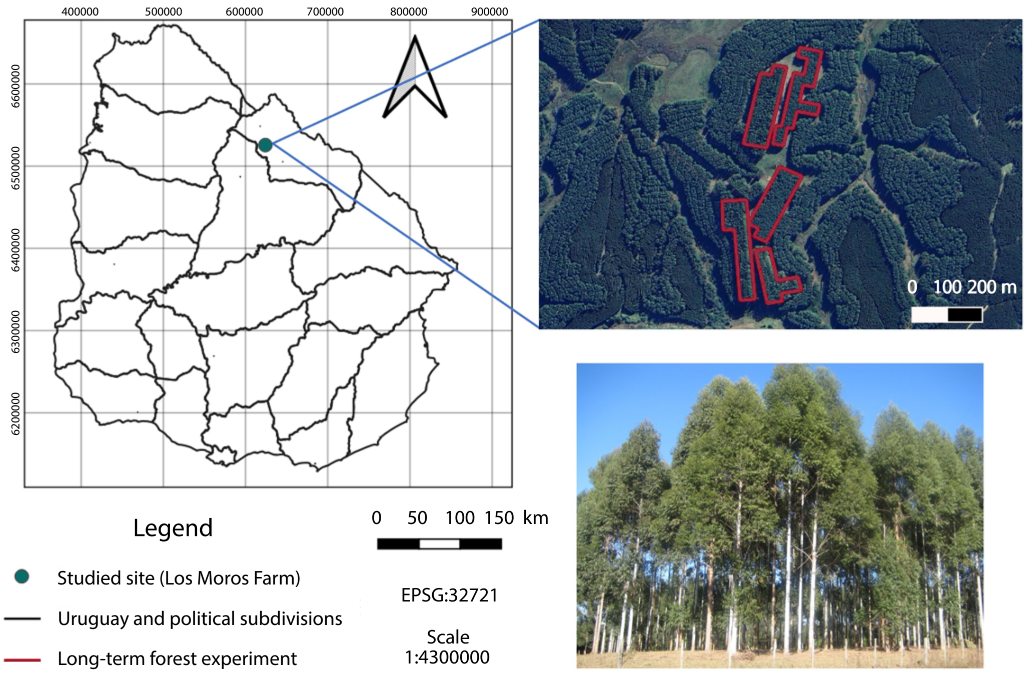


**Figure 1.** Location of the experimental site.

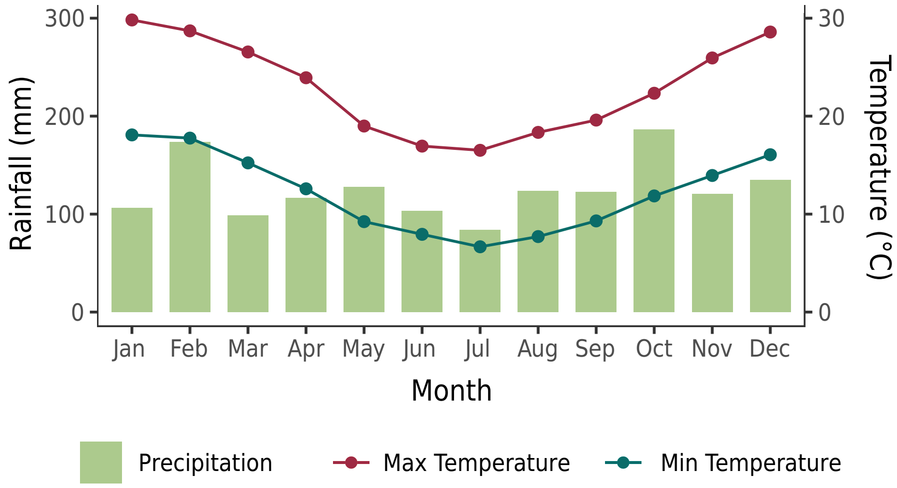


**Figure 2.** Monthly distribution of mean accumulated rainfall, and monthly mean maximum and minimum temperature.

The area is characterized by a temperate climate with an average temperature of 17.6 °C and an average annual accumulated rainfall of 1498.3 mm (INIA GRAS, 2023). Climate in the region is classified as Cfa according to Köppen-Geiger classification system (Kottek et al., 2006). Detailed information on monthly temperature and precipitation distribution is presented in figure 2. Soils at the site are developed from aeolian sedimentary rocks of Jurassic age, composed mainly of fine to medium sandstones (Montaño et al., 1998). Geomorphology is characterized by non-rocky sedimentary hills with slopes ranging from 10 to 15 %. Native vegetation is composed of predominantly summer cycle herbaceous communities dominated by C4 grasses such as *Andropogon* spp., *Axonopus* spp., *Paspalum* spp., *Sporobolus* spp., *Coleorhachis* spp., *Setaria* spp., *Panicum* spp., *Agrostis* spp., and *Eragrostis* spp.; some winter C3 grasses such as *Briza* spp. and *Piptochaetium* spp.; and some legumes such as *Adesmia* spp., *Arachis* spp., *Desmanthus* spp., *Desmodium* spp., *Macroptillum* spp., *Mimosa* spp., and *Trifolium* spp. (Bemhaja and Berretta, 2006). Stocking rate in the surveyed pasture area was 0.75 cows $ha^{-1}$.

Dominant soils in the experimental area are coarse-loamy, siliceous, active, thermic Humic Hapludults (Soil Survey Staff, 2014); Albic Alisols according to the World Reference Base for Soil Resources classification system (IUSS Working Group WRB, 2015). Table 1 presents detailed information about the edaphological characteristics of the site. The surface of the experiment and surrounding sampled areas belong to the same cartographic unit on a previously conducted detailed soil map and can be considered homogeneous in terms of soil texture.

**Table 1.** Properties of A, AB and B horizons from nine soil profiles (mean and standard deviation)[(1)]

| Hor | | Layer | Clay | Silt | Sand | pH | | SOC | $Al^{3+}$ | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ | Total bases | CECe | Base Sat. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | m | g $kg^{-1}$ | | | $H_2O$ | KCl | (g $kg^{-1}$) | cmolc $kg^{-1}$ | | | | | | | % |
| A | Mean | 0.00-0.48 | 126 | 54 | 820 | 4.7 | 3.8 | 9.36 | 1.6 | 1.33 | 0.78 | 0.26 | 0.35 | 2.73 | 4.33 | 63 |
| | Std. D. | | | | | 0.1 | 0.1 | 1.82 | 0.45 | 0.32 | 0.17 | 0.05 | 0.05 | 0.51 | 0.61 | 9 |
| AB | Mean | 0.48-0.66 | 233 | 87 | 681 | 4.7 | 3.8 | 7.37 | 2.14 | 1.39 | 0.77 | 0.22 | 0.40 | 2.78 | 4.92 | 58 |
| | Std. D. | | | | | 0.1 | 0.1 | 2.21 | 0.87 | 0.32 | 0.21 | 0.05 | 0.02 | 0.52 | 1.04 | 12 |
| Bt | Mean | 0.66-0.90 | 342 | 116 | 543 | 4.7 | 3.7 | 7.15 | 4.01 | 2.08 | 1.31 | 0.26 | 0.43 | 4.08 | 8.09 | 51 |
| | Std. D. | | | | | 0.1 | 0.1 | 1.23 | 1.36 | 0.33 | 0.34 | 0.06 | 0.07 | 0.67 | 1.71 | 9 |

[(1)] Reprinted from Hernández et al. (2016), with permission from Elsevier. SOC: soil organic C by Walkley–Black method; Extractable Al: extracted by KCl 1 mol $L^{-1}$; Extractable bases ($Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$): extracted by Ammonium Acetate 1 mol $L^{-1}$; CECe: effective Cation Exchange Capacity; Base Sat.: (Total Bases/CECe) 100; pH: soil: solution ratio of 1:2.5 (v:v). Std. D.: standard deviation.

## Long-term forest experiment description

Long-term forest experiment involved a combination of two tree species, *Eucalyptus grandis* and *Pinus taeda*, and three initial planting densities of 816, 1111, and 2066 trees $ha^{-1}$. Experiment was arranged in a randomized complete block design with three replications. At the time of sampling, the trees in the experiment were 13 years old. Each experimental plot was 1,000 $m^2$ in size, and the plots corresponding to the replications of each treatment were spaced at an average distance of 300 m apart from each other. Selected tree species and planting densities evaluated represent the region's forest production. Moreover, the previous vegetation of the site comprised natural grasslands, which allows to evaluate the impact of land-use change on these properties.

## Soil sampling and laboratory analyses

A randomized soil sampling was conducted in each of the plots of the forest experiment, corresponding to the three replications of each combination of tree species and initial planting density. Specifically, seven undisturbed soil cores, measuring 3.0 cm in height and 5.4 cm in diameter, were collected from the mineral soil surface in inter-row areas of each experimental unit, resulting in 126 samples representing the soil under forest cover. Before sample collection, the material corresponding to the Oi horizon (forest litter) was removed, leaving the fragmented and partially decomposed residues (Oe horizon) on the samples to avoid disturbing their surface. This fraction was then carefully removed in the laboratory before the hydrophobicity measurement. Additionally, 20 samples were collected from surrounding natural grasslands, enabling a comparison of the results obtained in the forest experiment with a pristine land-use condition to determine the effect of land-use change on the development of surface hydrophobicity. Sampling campaign was conducted in a single day during autumn 2017, and all samples were extracted using metal rings. Samples were refrigerated at 4 °C until laboratory processing to reduce bacterial and fungal activity.

Prior to the hydrophobicity assessment, the surface of the corresponding soil samples was carefully prepared by extracting the Oe horizon to expose the interface between the A and O horizons. Samples were kept undisturbed to assess hydrophobicity on a surface with the same physical properties as those found in the field. Soil water repellency was determined using the WDPT method (Letey, 2001) on samples that were previously equilibrated at -10, -33, and -100 kPa potential in ceramic plates (Klute, 1986). Five droplets of approximately 80 µL of deionized water were placed on the exposed A-O horizon interface using a dropper, and the elapsed time for complete infiltration was measured. This interface was chosen for evaluation as it is the zone of the soil profile that undergoes the greatest modifications in C dynamics associated with the land-use change under analysis (Hernández et al., 2016), and therefore, where the greatest modifications in the physical properties linked to this dynamics are expected. The WDPT measurement for each sample was obtained by averaging the infiltration time of the five droplets. According to Hallin et al. (2013), the number of drops required varies depending on droplet size to correctly classify soil hydrophobicity and define the mean WDPT value with 95 % confidence. With a droplet size of 80 µL, measuring four drops is sufficient to define the hydrophobicity class with 95 % confidence, while approximately 30 drops of 80 µL should be measured to correctly estimate the mean WDPT ± 10 % with 95 % confidence, which is a lower value than the measurements made in each experimental unit.

The WDPT test was selected due to its simplicity and because it does not require advanced laboratory equipment. Previous studies have demonstrated its strong correlation with more complex measurements of soil water repellency severity (Badía et al., 2013; Takawira et al., 2014; Miller et al., 2017; Jiménez-de-Santiago et al., 2019). This allowed to take a higher number of measurements. An administrative grouping was established to determine the order in which the samples were measured. In each batch, one sample from each plot was dried and measured.

The weight of each sample was measured after reaching equilibrium at -10, -33, and -100 kPa potential, prior to the determination of soil water repellency. After determining the hydrophobicity at -100 kPa, each sample was divided into halves. One half was stratified to obtain a subsample from the upper 1 cm, and the SOC content was determined using the Mebius (1960) method. The other half of the sample was weighed to calculate an "m" coefficient (total sample mass divided by divided sample mass) and then dried at 105 °C for 48 h. Total dry mass of the sample was estimated by multiplying the divided sample dry mass by the "m" coefficient. Soil water retention capacity was characterized by determining the Gravimetric Water Content (GWC) at each matric potential level, which was calculated by the difference between the wet and dry mass, relative to the dry mass.

## Statistical analysis

The effect of forest species and planting density on WDPT was assessed using a factorial model with two levels for the forest species (*E. grandis* and *P. taeda*) and three levels for planting density (816, 1111, and 2066 trees $ha^{-1}$). The analysis was conducted using generalized linear models (GLMs) with a logarithmic link function due to the asymmetric gamma distribution of WDPT, which is strongly right-skewed. The statistical model can be expressed by equation 1.

$$\log E(Y_{ijklm}) = \beta_0 + \alpha_i + \gamma_j + (\alpha\gamma)_i + \beta_k(\alpha_i) \qquad \text{Eq. 1}$$

in which: $E(Y_{ijklm})$ is the expectation of the dependent variable (WDPT); $\beta_0$ is the model intercept; αi is the forest species effect; $\gamma_j$ is the planting density effect; $(\alpha\gamma)_{ij}$ is the forest species by planting density interaction effect; $\beta_k(\alpha_i)$ is the replication within forest species effect. The WDPT was measured at *l* plot and *m* subsample level. An individual analysis was conducted for each soil matric potential (SMP) level (-10, -33 and -100 kPa), treating them as separate experiments.

To assess the impact of forest species and initial planting density on the rate of change in soil water repellency with variations in SMP levels, we used the ratio of WDPT at -100 and -10 kPa, as well as the ratio of WDPT at -100 and -33 kPa as explanatory variables. These variables were analyzed with the statistical model 1.

Additionally, 95 % confidence intervals were constructed for the mean of WDPT under forest use and under each evaluated forest species (*Pinus taeda* and *Eucalyptus grandis*), as well as for the average of WDPT under the natural pastures sampled in the surrounding areas of the experiment. The effect of the land-use change from native grasslands to forest plantations on soil water repellency was assessed by comparing these confidence intervals at each SMP.

To assess the impact of land-use change on the surficial mineral soil water holding capacity at different SMP levels, Mann-Whitney U tests were conducted by comparing the mean values of soil GWC under natural pastures and under forest cover, as well as under each of the forest species evaluated. Additionally, Spearman's linear correlation coefficients were calculated to identify associations among WDPT, GWC, and SOC at different SMP levels.

All statistical analyses were performed using R software (R Development Core Team, 2021). Generalized mixed linear models were fitted using the 'lme4' package (Bates et al., 2015), and data were visualized using the 'ggplot2' package (Wickham, 2016). Differences were considered significant at $p<0.05$ for all parameters and as a trend at.

### Bootstrapping analysis

Soil water repellency is a highly variable property that can exhibit significant spatial variability over short distances (Hallin et al., 2013; Šimkovic et al., 2022). Bootstrapping technique was used to determine if the sample size was sufficient to generate robust inferences. Specifically, an iterative resampling process with replacement was conducted, whereby two, three, and four of the seven samples collected from each plot in the forest density trial were randomly selected. Each of these three trials was conducted for each SMP (-10, -33 and -100 kPa) and repeated 5000 times. In each iteration, Model 1 was applied, and the average soil WDPT value for each forest species was calculated. Finally, the population of mean WDPT values obtained under each forest species was graphically analyzed, and the probability of a mean WDPT value belonging to the two populations (*Eucalyptus grandis* and *Pinus taeda*) was determined. Bootstrapping technique has proven its efficiency in estimating population parameters and determining optimal sample sizes in soil studies as demonstrated by its successful application in research conducted by Han et al. (2016) and García-Gutiérrez et al. (2018). Notably, this technique does not require prior knowledge of the distribution of the variable, as highlighted by previous studies (Dane et al., 1986; Johnson et al., 1990).

## RESULTS

### Effects of land-use and forest planting density on soil water repellency

Results from model (1) revealed that WDPT was significantly different between *E. grandis* and *P. taeda* cover across all evaluated SMP levels (Figure 3). Under *E. grandis*, hydrophobicity was found to be 1.60 ($p<0.001$), 1.95 ($p<0.001$), and 4.04 ($p<0.001$) times higher than under *P. taeda* at -10, -33, and -100 kPa potential, respectively. However, planting density did not have a significant effect on WDPT ($p = 0.74$ at -10 kPa; $p = 0.26$ at -33 kPa; and $p = 0.22$ at -100 kPa).

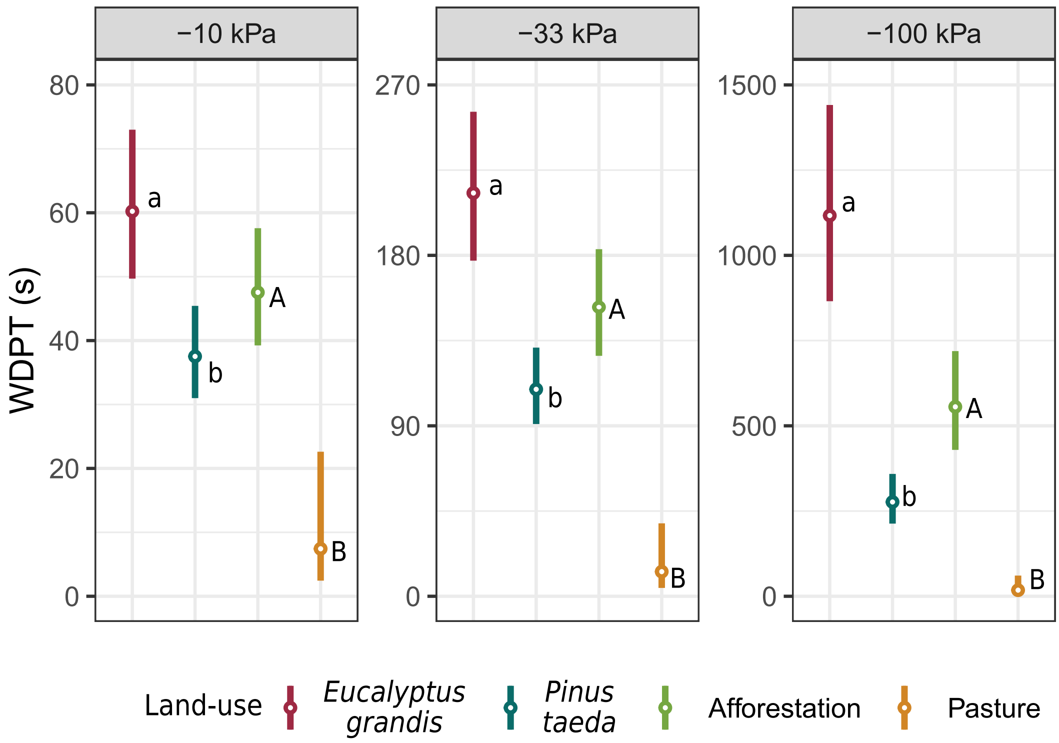


**Figure 3.** Confidence intervals for the mean WDPT according to soil matric potential (SMP) level and land-use. Different lowercase letters indicate significant differences between forest species ($p<0.05$) at each SMP level, and different capital letters indicate no overlapping of the confidence interval between land-uses (Afforestation vs. pasture).

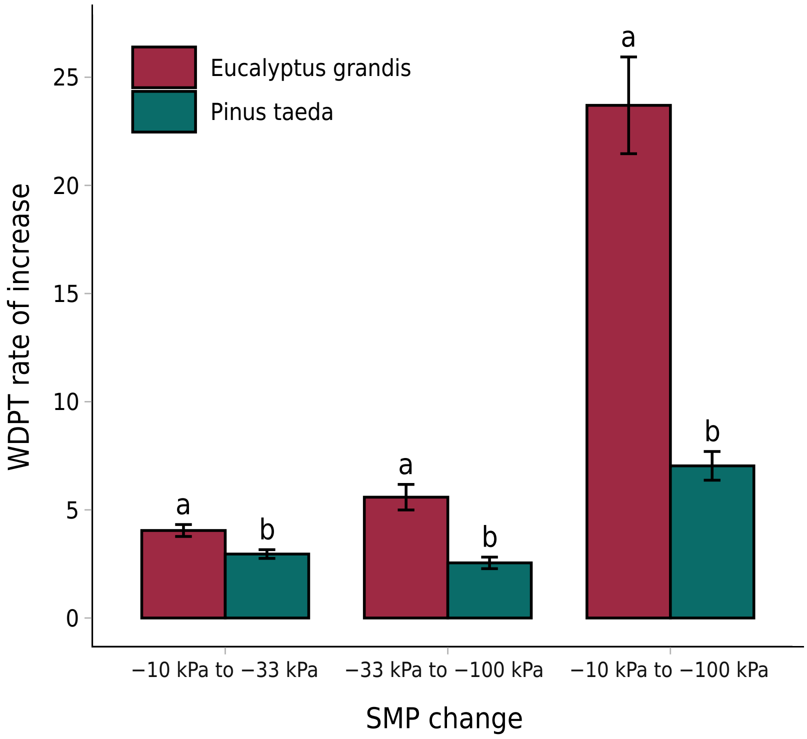


**Figure 4.** Soil surficial hydrophobicity (WDPT) rate of increase according to soil matric potential (SMP) change and forest species. Different letters indicate significant difference (p<0.05) at each SMP change level.

Soil water repellency increased as the soil dried (decrease in SMP), for both forest species (Figure 3). However, the rate of increase in soil water repellency with soil drying varied significantly between soils under different forest covers (Figure 4).

The WDPT increase rate between -10 and -100 kPa was significantly higher in soils under *E. grandis* compared to those under *P. taeda* ($p<0.001$), with an average value of 23.7 and 7.03, respectively (Figure 4). Similarly, significant differences were found in the increase rate in soil water repellency between -33 and -100 kPa potential when comparing the two forest species ($p<0.001$), with an average of 5.59 for *E. grandis* and 2.59 for *P. taeda* (Figure 4).

Land-use change from natural pastures to forest plantations significantly increased soil water repellency (Figure 3). The WDPT values under forest cover were 6.4, 11.7, and 31.7 times higher than under pastures at -10, -33, and -100 kPa potential, respectively. When the two forest species were considered separately, the mean WDPT value under *Pinus taeda* was 5.1, 8.4, and 15.7 times higher than under pastures at -10, -33, and -100 kPa potential, respectively. Similarly, soil hydrophobicity under *Eucalyptus grandis* was found to be 8.2, 16.4, and 63.8 times higher than under pastures at -10, -33, and -100 kPa potential, respectively.

### Relationship between soil water repellency and SOC content

Soil organic carbon content was significantly different between forest species ($p<0.01$) in the analyzed layer (uppermost 1 cm), being 4.60 ± 1.84 % under *Eucalyptus grandis* and 3.07 ± 1.52 % under *Pinus taeda*. This effect of the forest species on SOC aligns with the observed differences in surface hydrophobicity, which was considerably higher under *Eucalyptus grandis* than under *Pinus taeda*. Spearman's linear correlation analysis between soil water repellency (WDPT) and soil organic carbon (SOC) content for all soil samples under forest cover showed a positive and significant correlation with values of 0.55 ($p<0.01$), 0.44 ($p<0.01$), and 0.37 ($p = 0.01$) for -10, -33, and -100 kPa potential, respectively. In soils exclusively under *Pinus taeda*, the association was slightly lower, with a positive and significant correlation at -10 kPa (0.42; $p = 0.05$), but non-significant correlations at -33 kPa (0.32; p = 0.14) and -100 kPa (0.34; p = 0.11). Similarly, the relationship between WDPT and SOC in soils under *E. grandis* showed a significant Spearman's linear correlation coefficient of 0.58 (p<0.01) at -10 kPa, and non-significant correlations at -33 kPa (0.33; p = 0.14) and -100 kPa (0.02; p = 0.92). Relationship between SOC content and the rate of increase in soil water repellency with decreasing SMP was not significant in any of the considered forest covers.

### Effect of land-use change on the surficial soil water holding capacity and its relationship with hydrophobicity development.

Conversion of native pastures to forest cover significantly impacted the soil surface water holding capacity. This was evidenced by reductions in GWC of 9.27, 16.5, and 24.6 % at -10, -33, and -100 kPa SMP, respectively (Figure 5a). When evaluating the substitution of pastures for *P. taeda* plantation, the results were similar, corresponding to significant reductions of 15.9, 22.4 and 28.5 % at -10, -33 and -100 kPa, respectively (Figure 5b). However, changing from pastures to *Eucalyptus grandis* plantation led to a reduction in water retention capacity of 10.5 and 20.4 % at -33 and -100 kPa SMP, respectively, but no significant reduction or trend was observed at -10 kPa SMP (Figure 5c).

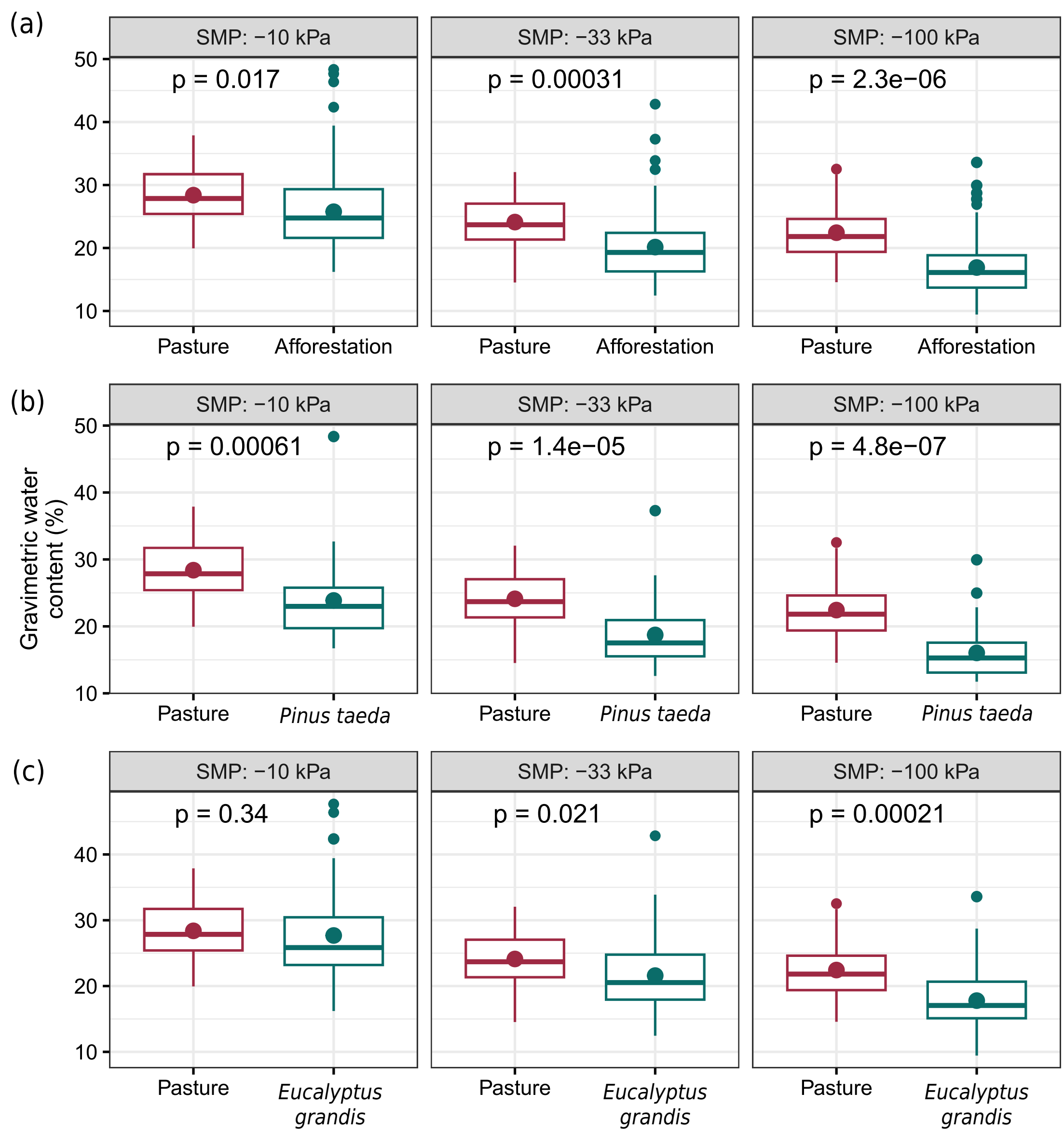


**Figure 5.** Soil gravimetric water content (GWC) according to soil matric potential (SMP) and land-use (a: Pasture vs. Afforestation; b: Pasture vs. *Pinus taeda*; c: Pasture vs. *Eucalyptus grandis*). p is the Mann-Whitney test p-values for each comparison.

**Table 2.** Spearman's linear correlation coefficients between gravimetric water content (GWC) and water drop penetration time (WDPT) at different soil matric potential (SMP) levels for different sample sets

| Sample set | Soil Matric Potential | | |
|---|---|---|---|
| | -10 kPa | -33 Kpa | -100 kPa |
| Afforestation + Pasture | -0.01 (p=0.88) | -0.13 (p=0.13) | -0.22 (p<0.013) |
| *Eucalyptus grandis* + Pasture | -0.10 (p=0.39) | -0.26 (p<0.026) | -0.48 (p<0.01) |
| *Pinus taeda* + Pasture | -0.16 (p=0.18) | -0.28 (p=0.017) | -0.33 (p<0.01) |

Spearman correlation analysis was evaluated between WDPT and GWC balanced at different SMP levels (Table 2). In the case of all soil samples analyzed from both forest cover and native pastures, a negative and significant correlation coefficient of -0.22 was found at -100 kPa, but no significant relationship was observed at -10 and -33 kPa. However, for the soil samples from *E. grandis* cover and native pastures, the correlation between the two variables was stronger, with coefficients of -0.26 and -0.48 at a level of -33 and -100 kPa SMP, respectively. Association was weaker for soils under *P. taeda* and pastures, with coefficients of -0.28 and -0.33 at -33 and -100 kPa SMP, respectively.

### Bootstrapping analysis

Figure 6 shows the distributions of 5000 means of WDPT under the two forest species examined in each of the bootstrap analyses conducted. When subsampling at a SMP of -10 kPa, the probability that the mean of WDPT for both species belonged to the same population was 29.3 % for a sample size of 2 in the bootstrapping procedure, 2.6 % for a sample size of 3, and 4.07e-5 % for a sample size of 4. At a SMP of -33 kPa, the corresponding probabilities were 10.9, 0.55, and 1.2e-7 %, respectively, for sample sizes of 2, 3, and 4. Lastly, at a SMP of -100 kPa, this probability for a sample size of 2 was 2.8e-6 %, while no overlap between the bootstrapped means of both species was observed for sample sizes of 3 and 4.

## DISCUSSION

After converting native pastures to *Eucalyptus grandis* forest plantations, soil water repellency showed a greater increase compared to *Pinus taeda* plantations, according to a long-term forest experiment conducted 13 years after land-use change (Figure 3). This finding aligns with previous studies (Zavala et al., 2009; Benito et al., 2019; Piyaruwan et al., 2020) that have also reported a higher occurrence of soil water repellency in forest soils covered by *Eucalyptus* sp. compared to those covered by *Pinus* sp. However, it is important to note that these previous studies were conducted in soils that were not originally covered by native pastures or were not located in a temperate humid climate.

Several authors have proposed that the higher levels of soil hydrophobicity developed under *Eucalyptus* sp. would be due to the type of organic matter generated by these species, which has a greater hydrophobic nature, or as a consequence of higher rates of accumulation of these substances in the soil (Doerr et al., 1996). Concentration of free lipids plays a significant role in soil water repellency under forest covers of *Eucalyptus* sp. and *Pinus* sp. species (Blas et al., 2010). These free lipids form hydrophobic covers around soils particles, and their molecular composition depends on the vegetation type. In soils under *Eucalyptus* sp. cover, sesquiterpenes and some specific monoterpenes are the main components of the free lipid fraction, whereas in soils under *Pinus* sp. cover, it is mainly composed of fatty acids and diterpenes (Blas et al., 2013). In contrast to the high concentration of waxes, cutin, suberin, and terpenoids present in the SOM under forest covers (Blas et al., 2013), soils developed under pastures contain low amounts of aromatic C compounds and high concentrations of products rich in O-alkyl radicals derived from the decomposition of easily decomposable residues with a lower proportion

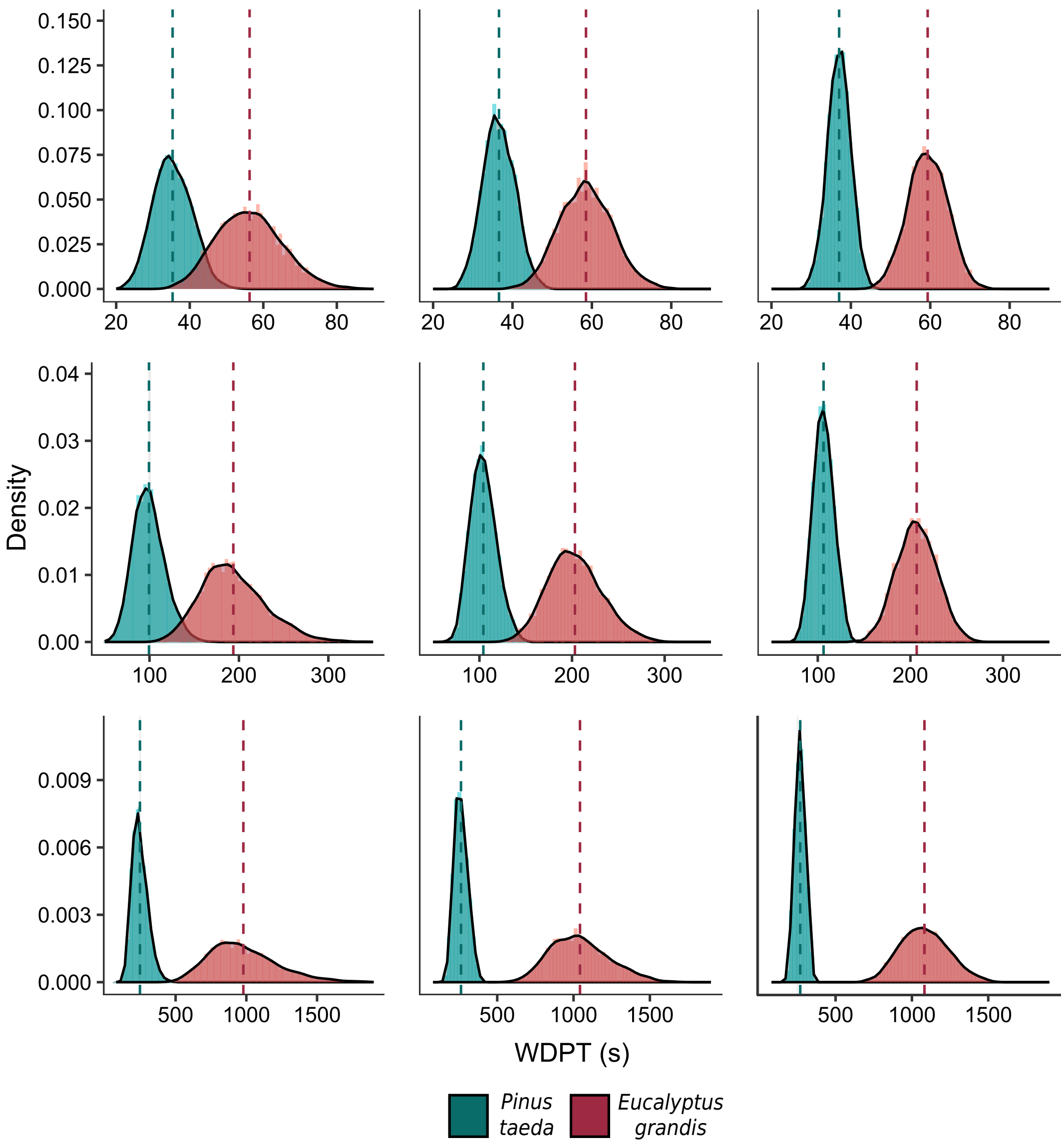


**Figure 6.** Populations of bootstrapped means of soil surficial hydrophobicity (WDPT) in 5000 resamples of size 2, 3 and 4, at different SMP (soil matric potential) and under different forest species. Dashed lines indicate the general mean for each species of the 5000 iterations.

of lignin and recalcitrant lipids, and with a high concentration of carbohydrates (Mendham et al., 2002; Pérez-Cruzado et al., 2014).

Higher soil water repellency observed under *Eucalyptus grandis* could be linked to a higher accumulation rate of organic compounds, including the hydrophobic substances previously mentioned. This hypothesis is consistent with the findings of Crockford and Richardson (1998) and Demessie et al. (2012), who reported higher annual litter production in *Eucalyptus* sp. plantations compared to coniferous species. Furthermore, Rodríguez-Alleres et al. (2007) suggest that the higher transpiration rates of *Eucalyptus* sp. may lead to greater soil drying during periods of water deficit, resulting in higher precipitation of organic compounds around soil particles.

Surficial soil hydrophobicity was not affected by the planting density. This is consistent with previous findings by Hernández et al. (2016), who evaluated eight-year-old *Pinus taeda* and *Eucalyptus grandis* plantations in north-eastern Uruguay and found no significant differences in soil organic carbon content among different planting densities (816, 1111, and 2066 trees ha$^{-1}$). The compensation of aerial tree biomass by decreasing the planting density leads to the development of wider treetops, resulting in similar amounts of organic matter capable of supplying hydrophobic compounds to the soil in forest plantations with different initial densities (Bhandari et al., 2021; Gabira et al., 2023). Therefore, the absence of identified differences in hydrophobicity when comparing different forest planting density treatments is consistent with these previous findings.

Comparison of WDPT results from the forest experiment with surrounding native grasslands shows land-use change from native pastures to forest plantations led to an increase in soil surface hydrophobicity (Figure 3) detectable in 13 years. This increase in hydrophobicity was 6.4 times when evaluated at -10 kPa and 31.7 times when evaluated at -100 kPa. Previous studies have claimed that the main factor determining surface hydrophobicity development is vegetation cover (Letey, 2001; Rodríguez-Alleres et al., 2007; Benito et al., 2019), and many of these studies associate soil water repellency with forest covers that produce large amounts of resins, waxes, and aromatic oils that are deposited on the soil (Doerr et al., 2000; Verheijen and Cammeraat, 2007; Piyaruwan et al., 2020). These hydrophobic compounds are highly resistant to decomposition and tend to accumulate on the soil surface due to the characteristic distribution of organic matter in forest soils, contributing to the development of soil water repellency in the uppermost layer of the soil profile. Moreover, many studies suggest that soil water repellency is strongly influenced by the activity of soil organisms, among which fungi play a prominent role (Rillig, 2005; Lozano et al., 2013; Seaton et al., 2019). Specifically, Lozano et al. (2013) argue that some forest covers lead to a shift in the microbial environment that accentuates the synthesis of certain hydrophobic substances, such as long-chain lipids and glomalin (Rillig, 2005). Land-use change from grassland to forest covers would promote the accumulation of these substances due to an increase in fungal activity primarily associated with an increase in the C:N ratio of carbon inputs to the system (Kuijper et al., 2005). Although several studies have investigated the development of soil hydrophobicity in forest systems, information on the development of soil water repellency under forest plantations that replace native pastures is limited. Replacing native pastures with forest plantations significantly modifies soil water properties, resulting in measurable changes in soil water repellency 13 years after the vegetation change.

A positive association between WDPT and SOC content was observed; however, the strength of the association was not particularly high. Therefore, it is suggested that changes in the composition of soil organic matter resulting from land-use change may be more significant in explaining the observed changes in soil water repellency than variations in the overall amount of organic matter. This result is consistent with the findings of previous studies (Woche et al., 2005; Rodríguez-Alleres et al., 2007). The greater importance of SOC quality over quantity in determining hydrophobicity could also explain the lack of effect of forest plantation density on soil water repellency, even though the forest species was significant.

Regarding the SMP, soil hydrophobicity increases progressively as the soil dries to more negative potentials (Figures 3 and 4). Previous studies have found hydrophobicity varies with soil water content, reaching maximum values when soil is dry, but decreasing or even disappearing after intense precipitation or during extended periods of high water content (Butzen et al., 2015; Vogelmann et al., 2017). It has been suggested that there would be a reorientation of amphipathic hydrophobic substances when soil moisture content increases, resulting in a decrease in the overall water repellency of the soil matrix (Doerr and Thomas, 2000; Mainwaring et al., 2013). In these previous studies, the relationship between hydrophobicity and water content was evaluated in situ, or by air drying or oven drying soil samples for different periods and at different temperatures. However, in the present study, the soil moisture corresponding to different retention energies was fixed to reduce the variability generated by the previously listed alternative strategies.

Land-use change from natural pastures to forest plantations resulted in a shift in the soil water holding capacity at different SMP (Figure 5). After 13 years of replacing the natural pasture cover with forest plantations of the two species evaluated, a decrease in the GWC in equilibrium at -10, -33, and -100 kPa matric potential of soil surface layer was observed (Figure 5). This effect was more pronounced at more negative SMP, with a higher significance of the statistical test and a larger relative distance between the corresponding average values. Moreover, a negative correlation between WDPT and GWC was observed, which was weak at high moisture contents and became more significant when evaluated in a drier soil (SMP = -100 kPa) (Table 2). These findings are consistent with physicochemical models proposed to explain the development of soil water repellency (Doerr and Thomas, 2000; Mainwaring et al., 2013). As the moisture content decreases, the progressive reorientation of amphipathic molecules around soil particles exposes their nonpolar tails towards the solution, reducing the ability of soil colloids to attract water molecules. This process alters the soil matric potential from its physicochemical base and decreases water retention capacity, which is accentuated at highly negative SMP levels. This would be the mechanistic link between the observed dynamics of soil water retention and hydrophobicity as a function of the SMP.

Physicochemical mechanisms previously outlined (Doerr et al., 2000; Mainwaring et al., 2013) also explain the significant effect of forest species on the rate of hydrophobicity change with soil moisture variations (Figure 4). Soils with higher levels of hydrophobic compounds due to vegetation cover (*Eucalyptus grandis*) are expected to have a greater capacity to increase hydrophobicity through the reorientation of amphipathic substances with moisture decrement, compared to those with other types of coverage (*Pinus taeda*).

Finally, the results presented in this study are robust despite the large variability of soil hydrophobicity (Hallin et al., 2013; Šimkovic et al., 2022). A resampling and iterative analysis using bootstrapping to test the stability of differences in soil hydrophobicity between the two forest species showed that obtaining seven samples per plot of the forest trial was sufficient to reliably identify treatment differences (Figure 6). This analysis confirms that four samples per plot would have been adequate to obtain equivalent results.

## CONCLUSIONS

This study provides valuable insights into the impact of establishing forest plantations on native pastures in humid temperate regions. These findings are particularly relevant in the Río de la Plata grassland region, where this land-use change has been highly significant in recent decades.

Replacing native pastures with *Eucalyptus* sp. forest plantations results in greater surficial soil water repellency compared to *Pinus* sp. plantations, as observed in a long-term forest experiment 13 years after the land-use change. However, forest planting density did not affect soil hydrophobicity generation within the evaluated range, possibly due to a similar forest litter accumulation rate associated with a higher volume of individual canopies in lower densities. Comparison of WDPT results from the forest experiment with surrounding native grasslands shows land-use change from native pastures to forest plantations leads to a significant increase in soil surface hydrophobicity in 13 years.

A positive association between hydrophobicity and SOC content was found, though the low magnitude of this association indicates soil water repellency depends more on the type of carbon compounds than their total quantity. Results also suggest soil water repellency increases with decreasing SMP, and the rate of hydrophobicity increase depends on the initial level of soil water repellency. Soils under covers that determine greater hydrophobicity (*Eucalyptus* sp.) have more accelerated increasing rates of this property when drying.

Land-use change from natural pastures to forest plantations reduced the soil water holding capacity at different SMP, with the effect being more pronounced at more negative SMP. We propose that the reorientation of amphipathic substances around soil particles is responsible for the greater rate of increase in hydrophobicity of *Eucalyptus* spp. compared to *Pinus* spp., as well as for the decrease in soil water holding capacity under forest plantations compared to natural pastures, accentuated as the soil dries.

Application of bootstrapping procedures confirmed the robustness of the inferences, as the results regarding the effect of forest species on soil water repellency remained unchanged even when smaller sample sizes were used in sub-sampling experiments.

Future studies should assess the soil water repellency evolution over time by measuring soil hydrophobicity across varying periods following the land use change. Finally, it is also necessary to assess whether the observed changes in soil properties lead to a significant increase in soil hydrophobicity and a decrease in soil water holding capacity at greater depths in systems defined by a land-use change from native pastures to forest plantations in temperate climates. Such research will be crucial for understanding the long-term impacts of this land-use change on soil hydrology and ecosystem functioning.

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