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Hydrophysical characteristics in water-repellent tropical Eucalyptus, Pine, and Casuarina plantation forest soils

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Abstract: Soil water repellency (SWR) reduces the rates of wetting in dry soils and is known to interfere with water movement into as well as within the soils. The objective of this study was to investigate the hydrophysical characteristics of three water-repellent tropical exotic plantation forest soils in wet and dry seasons. The study sites were *Eucalyptus grandis* (EG), *Pinus caribaea* (PC), and *Casuarina equisetifolia* (CE) plantation forest soils located in the up-country intermediate zone (EG and PC), and low-country dry zone (CE). Field experiments were conducted to measure the infiltration rate, unsaturated hydraulic conductivity (k), water sorptivity (S_W). Laboratory experiments were conducted to measure the potential SWR and water entry value (h_{we}). All three soils showed higher SWR in the dry season, where CE soils showed the highest. The EG soils showed the highest SWR in the wet season. Although SWR in all soils decreased with increasing depth in the wet season, only CE soils showed a significant decrease in SWR with soil depth in the dry season. Compared with the wet season, the k(–1 cm) was lower and h_{we} was higher in the dry season. However, S_W did not show a significant difference between wet and dry seasons. Initial infiltration rate and k(–1 cm) showed a negative correlation with contact angle in all three soils. Soils showed positive linear correlations between k(–1 cm) and S_W, and negative linear correlations between S_W and h_{we} showing that surface water absorption is related to both subsurface unsaturated water flow and surface water entry pressure. It was clear that the water entry into soils and the subsurface water flow were hindered by the SWR. High water entry values in the dry season predict high potentials for intensified surface runoff and topsoil erosion. Future research will be required on the interactions between soil biology and soil properties such as pore structure that would influence water flow into and within soils.

Keywords: *Eucalyptus grandis*; *Pinus caribaea*; *Casuarina equisetifolia*; Hydrophysical characteristics; Water repellency.

INTRODUCTION

Soil water repellency (SWR) restricts the wetting of soils and may induce preferential flow paths resulting in irregular moisture or wetting patterns in soils (Šurda et al., 2020). SWR is caused by either the intermixed organic substances or organic coatings on the mineral soil particles of hydrophobic nature (DeBano, 1981; Hallett, 2007). The organic substances that are responsible for the development of SWR are usually considered to be plant roots, microbial exudates, surface waxes of leaves, and any other organic substances such as long-chain aliphatic acids, alcohols, wax esters (Bisdom et al., 1993).

The basic impact of SWR can be considered as the reduction of the rates of water infiltration into soils. Water repellency reduces the wetting rates in dry soils and lowers the plant available water, and is known to interfere with water movement into and within the soils affecting most of the hydrophysical properties and processes in soils (Lichner et al., 2012). SWR further leads to uneven patterns of water entry into soil generating unstable and irregular water flow within the soil matrix (Rodný et al., 2015). Hindered water entry into soils promotes surface runoff followed by intensified erosion, resulting in irregular moisture patterns in the soil. Localized high and less water-repellent zones lead to a selective water entry through the less water-repellent patches, stimulating preferential flow paths. Solute transport in soils through these specified flow channels can lead to accelerated transport of dissolved chemicals into groundwater (Lichner et al., 2013; Wessolek et al., 2008).

SWR has long been considered a widespread challenge to plant growth in many regions (Doerr et al., 2000). It is not limited to specific climates or soil types, and is reported in numerous types of land uses throughout the world. Water repellency is repeatedly observed in soils covered by tree species such as Japanese cypress (*Chamaecyparis obtusa*), Japanese cedar (*Cryptomeria japonica*), eucalyptus (*Eucalyptus grandis, Eucalyptus globulus*), pine (*Pinus sylvestris, Pinus pinaster, Pinus caribaea*), and casuarina (*Casuarina equisetifolia*), which are rich in various types of hydrophobic resins and waxes (Benito et al., 2019; Doerr et al., 1996; Iovino et al., 2018; Kobayashi and Shimizu, 2007; Keizer, et al., 2008; Leelamanie, 2016; Lichner, et al., 2013; Piyaruwan et al., 2020). Water-repellent phenomena observed in these specific forests are known to be natural circumstances rather than being induced by different external aspects such as forest fire conditions. This vegetation-induced SWR is usually associated with chemical compounds such as alkanoic acids, alkanes, and esters (Hansel et al., 2008).

Forests with SWR conditions are reported to have altered soil hydraulic properties (Kobayashi and Shimizu, 2007; Letey et al., 1962; Lichner et al., 2013; 2020; Wahl et al., 2003). Numerous impacts of SWR on soil water systems have been recognized by studies under different land-use types and climatic regions. SWR tends to be highly variable spatially as well as temporally, where it often disappears following prolonged wet periods. Intensified surface runoff and erosion in water-repellent soils are reported with heavy rainfall events usually

following long dry and hot periods (Onderka et al., 2012; Pavelková et al., 2012). Inherent water-repellent characteristics in soils under different types of tree species are known to influence soil hydrological processes more specifically following longer hot or dry spells (Lichner et al., 2012).

Forest plantations in Sri Lanka were mainly established using non-native species such as Eucalyptus, Pine, and Casuarina due to their faster growth rates over the indigenous species. The idea of this exercise was to have an alternative timber resource to protect the existing natural forest and to rehabilitate the environmentally damaged areas within a short period. However, these plantations created a dialogue over its unsuitability as demonstrated by the natural evidence, such as drying out of streams, reduction of groundwater level, the nonexistence of undergrowth, and lack of animal diversity, including the presence of SWR (Leelamanie 2016; Piyaruwan and Leelamanie, 2020; Piyaruwan et al., 2020). Although these plantations have proven to have some of the expected advantages, the water-repellent aspects and their hydrophysical consequences are yet to be explored comprehensively. The objective of this study was to investigate hydrophysical characteristics of three water-repellent tropical exotic plantation forest soils (Eucalyptus, Pine, and Casuarina), considering both rainy (wet) and dry seasons.

MATERIALS AND METHODS

Study area

The study was conducted at three water-repellent experimental sites, namely *Eucalyptus grandis* (EG), *Pinus caribaea* (PC), and *Casuarina equisetifolia* (CE) plantation forest soils. The EG forest (06°47'45" N 80°57'58" E) and the PC forest (06°46'13" N 080°55'52" E) were located in the up-country intermediate zone (EG: IU3c; PC: IU3a, IU3b agro-ecological regions), whereas the CE forest is located (6°06′52″ N 81°05′02″ E) in low-country dry zone (DL5 agro-ecological region) (National Atlas of Sri Lanka, 2007).

The first experimental site, EG forest (~100 ha) is in a slope land with considerably steep slopes ranging from ~10 to 35 °. The mean annual rainfall of the area is 1600–1700 mm. The highest rainfall is received in April and October to December (wet season), where February, June, July, and August are the dry months (dry season) receiving less than 10% of the average annual. The mean annual temperature is in a range of 20–22.5 °C. The soil is identified as Red Yellow Podzolic according to the local classification system (National Atlas of Sri Lanka, 2007) and Hapludults, according to the USDA classification system (Soil Survey Staff, 2014). A dense layer of litter (3–4 cm in thickness) was observed on the surface. The average field moisture content of soil in the wet and dry seasons were 12 and 8%, respectively.

The second experimental site, PC forest (~100 ha) was also located in a land with steep slopes ranging from ~10 to 40°. The mean annual rainfall of the area is 1700–1900 mm and the mean annual temperature is in a range of 20–22.5 °C. The highest rainfall in the area is received in March to May and October to December (wet season). February, June, July, and August are the dry months (dry season) receiving less than 10% of the average annual rainfall. Similar to the EG site, the soil of the area is classified as Red Yellow Podzolic under the local classification system and Hapludults under the USDA classification system. A 3–12 cm thick layer of litter consisting mostly of pine needles was observed on the surface. The average field moisture content of soil during the wet and dry seasons were 17 and 14%, respectively.

The third experimental site, the CE forest (~36 ha) is a sand dune in the Southern Dry zone, which is considered as one of the driest parts of Sri Lanka with an average annual rainfall of about 900 mm. About 70% of the annual total rainfall is received from mid-October to mid-January (wet season), and minor proportion during mid-March to mid-May. Mid-May to September is considered to be the dry period (dry season) receiving less than 20% of the annual rainfall. The average annual temperature varies from 25 to 31 °C, with the highest temperatures are recorded in the driest period of the year (May–September) (National Atlas of Sri Lanka, 2007). The soil type is identified locally as sandy Regosols, or according to USDA classification as Ustic Quartzipsamments. Sandy Regosols are soils that are in general found along or within proximity to the coastline, with no specific structural development, where both surface and subsurface soils are single-grained (National Atlas of Sri Lanka, 2007). Soil reaction is nearly neutral (pH: 7.4±0.2). The forest floor of the studied dune is covered with a thick mat of dry leaf litter layer or phylloclades (3–10 cm of thickness). The average field soil moisture content during the wet and dry seasons were 5–7% and 0.5–1.5%, respectively.

The litter layers at all three experimental sites vary in thickness interrelated with the climatic conditions, more specifically, the rainfall. The maximum litter thicknesses were observed in the driest periods, where the decomposition rate of the organic matter is very low. During these dry periods, extreme levels of water-repellent nature can be observed on the soil surfaces. During the rainy season, organic matter decomposition takes place at an accelerated rate and the thickness of the litter layer decreases. Simultaneously, the magnitude of water-repellent behavior also tends to drop. The thematic maps of normalized difference vegetation index (NDVI) for the three plantation forest sites that represent the greenness and the relative density of the vegetation covers are given in Figure 1. Most of the land area in all three study sites showed NDVI values above 0.5, indicating close to dense vegetation cover.

Soil sampling

Field experiments and laboratory experiments were conducted during the period from 2016 to 2020 dry (July, August) and wet (November, December) seasons in all three sites. After carefully removing the litter, both undisturbed core samples and bulk samples were collected from each site at the depths of 0–5, 5–10, and 10–15 cm for laboratory experiments. Nine sampling points were sleeted (about 2 m away from trees) per site to represent 3 blocks, in three replicates. The collected soil samples were tagged, sealed, and transported to the laboratory.

Laboratory experiments

In the laboratory, soils were air-dried at room temperature (27±3 °C) for 3 days and passed through a 2-mm sieve. The basic properties of the soils were measured in triplicates following standard laboratory procedures. The bulk density, the particle density, and the texture of soils were measured using the undisturbed soil core method (Blake and Hartge, 1986a), pycnometer method (Blake and Hartge, 1986b), and the hydrometer method (Bouyoucos, 1962), respectively. The organic matter content was measured using the loss on ignition (400 °C for 6 h) method (Rowell and Coetzee, 2003; Schumacher, 2002). The basic properties of the tested soils in the three experimental sites are given in Table 1.

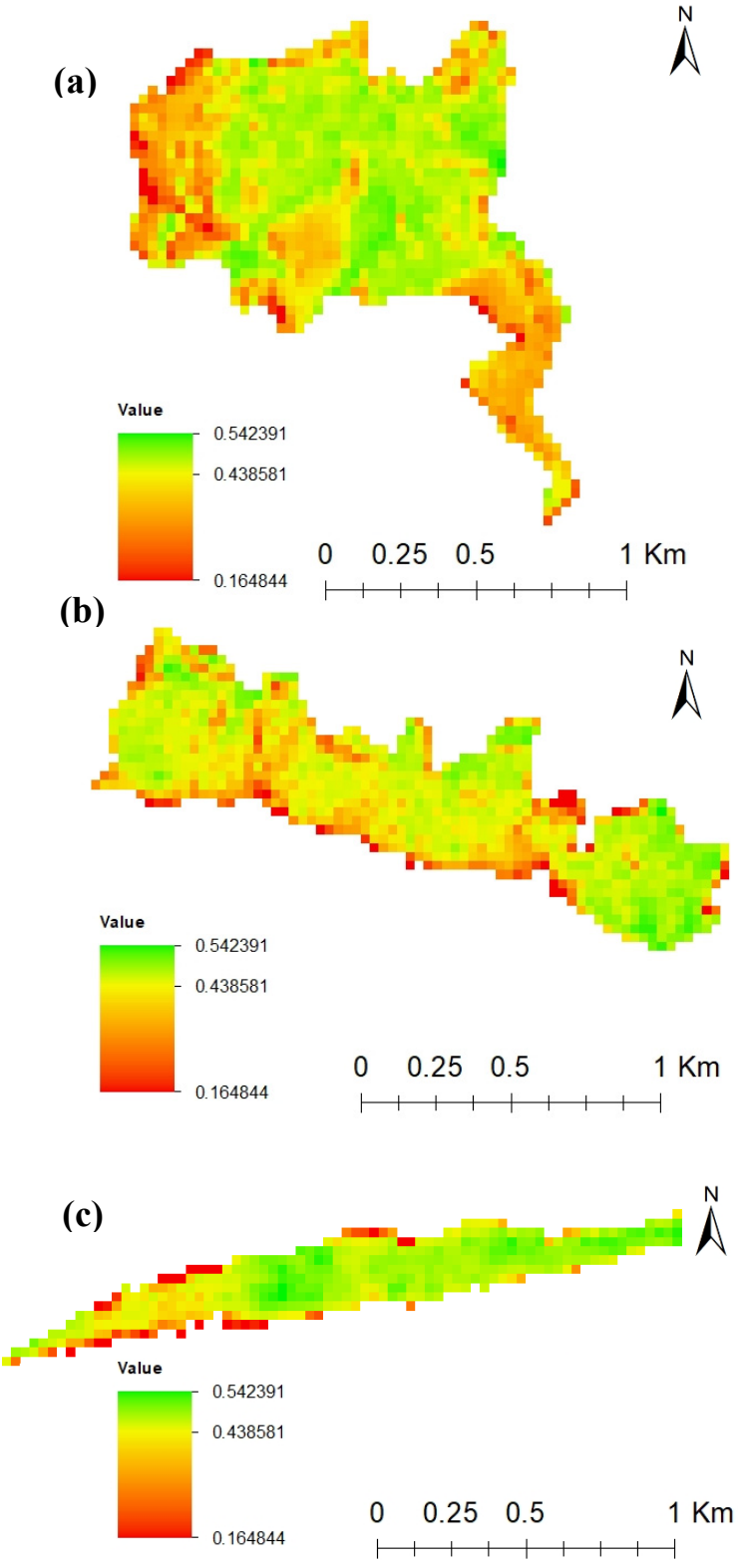


Fig. 1. Thematic maps of Normalized Difference Vegetation Index (NDVI) in 2020 for the (a) Eucalyptus, (b) Pine, and (c) Casuarina plantation forest sites.

Water repellency

The potential soil water repellency (SWR) was measured using the water drop penetration time (WDPT) and soil-water contact angle. Soil subsamples with a thickness of >5 mm were used for the WDPT test. Single drop (50±1 µL) of distilled water was placed on the surface of the soil from a height of about 10 mm using a burette. Containers were carefully covered with lids to minimize the effects of evaporation during the experiment. The time taken for water drops to completely penetrate the soil was measured using a stopwatch (Bisdom et al. 1993; Chenu et al., 2000; Leelamanie et al., 2008). Penetration

Table 1. The basic properties of the plantation forest soils (mean ± standard deviation).

Soil property		Eucalyptus			Pine			Casuarina		
		0–5 cm	5–10 cm	10–15 cm	0–5 cm	5–10 cm	10–15 cm	0–5 cm	5–10 cm	10–15 cm
Bulk density (g cm^{-3})		1.02±0.10	1.10 ±0.05	1.18 ±0.02	0.96±0.16	1.07±0.07	1.12±0.10	1.98 ±0.04	2.12 ±0.09	2.19 ±0.08
Particle density (g cm^{-3})		2.30±0.25	2.30 ±0.26	2.55 ±0.22	2.56±0.16	2.68±0.07	2.58±0.25	2.80 ±0.03	2.81 ±0.12	2.80 ±0.08
Porosity (%)		55.5 ±6.0	52.1±5.6	53.8±4.2	62.5±5.6	60.0±1.8	56.7±5.0	29.3±2.5	24.5±2.8	21.8±2.4
Sand %		80.4 ±1.8	74.8 ±2.1	79.5 ±0.1	73.7±3.9	72.6±2.3	72.6±3.2	96.7±2.1	96.9 ±4.1	97.0 ±2.9
Silt %		5.8±1.5	6.4±1.5	6.3±1.5	10.4±0.6	8.2±1.6	9.2±1.5	3.2±0.5	2.9±0.3	2.5±0.3
Clay %		13.8±4.2	17.8 ±4.4	14.2 ±2.4	15.9±3.7	19.3±3.4	18.2±1.9	0.1±0.05	0.2±0.3	0.5±0.2
Texture		Loamy sand	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Sand	Sand	Sand
Organic matter (%)	Wet	9.94±0.14	7.05 ±0.04	6.92 ±0.06	15.4±4.0	12.4±2.8	10.6±1.7	1.82 ±0.15	1.29 ±0.08	0.56 ±0.04
	Dry	13.2 ±1.1	9.83 ±0.72	7.95 ±0.74	19.1±1.6	15.5±1.1	12.4±0.4	2.04 ±0.06	1.64 ±0.03	1.17 ±0.03

times shorter than 0.5 s were considered as 0 s because the actual measurement could not be taken accurately corresponding to the instantaneous penetration. The measurement of penetration time was terminated after 6 h. The WDPT values were determined in three replicates for nine sampling points in each site.

The soil-water contact angle was measured using the modified sessile drop method (Bachmann et al., 2000) using a digital microscopic camera (FS-3100-PC, Fujikoden Co. Ltd., Japan). Monolayers of soil samples fixed on double-sided adhesive tapes (1.5 cm × 1.5 cm) using smooth glass slides were used for the measurements. A drop (10 µL) of distilled water was placed on the surface of soil monolayer using a micropipette (Nichipet EX II J15615241. Nichiriyo, Japan). A digital microphotograph of the water drop (horizontal view) was taken within 1–2 s. The contact angle was determined, in three replicates, using the digital micro-photographs of the horizontal view of the drop (Leelamanie, 2016).

Water-entry value

In water-repellent soils, low hydraulic pressures present on the soil surfaces are not sufficient to start the infiltration. Water starts to infiltrate into water repellent soils at a critical pressure showing an instantaneous breakdown of SWR (Wang et al., 2000). The critical pressure that is required for the breakdown of repellency and driving water into that soil can be determined using the water-entry value (h_{we}).

The h_{we} of the topsoil was tested in the laboratory, in triplicates, using the pressure head method (Wang et al., 2000), for the samples collected from the surface soils (0–5 cm). Air-dried soils, in 50-g soil subsamples, were placed in the Buchner funnel, where the porous plate was covered with a membrane filter and filter paper. The funnel was attached to a burette using a flexible tube. Increasing hydraulic pressure was applied to the soil sample using increasing water height by raising the burette level. The starting pressure head was kept negative to prevent initial wetting (Wang et al., 2000). The hydraulic pressure head was increased carefully by 5 min intervals up to the point where the water enters into the soil matrix. At this point of water entry, the height of the water column (burette water level compared to the reference level considering the soil) was recorded as the h_{we} of the samples (Liyanage and Leelamanie, 2016).

Field experiments

The actual SWR, infiltration rate, unsaturated hydraulic conductivity, k(–1 cm), and water sorptivity (S_W) of the soils in the forest soils were determined in the field. Sampling was conducted in triplicates, sectioning in the study area into three blocks (total of nine sample points), during wet and dry seasons.

The actual SWR was measured using the WDPT test by placing a drop (50±1 µL) of distilled water on the soil surface from a height of about 10 mm using a micropipette (Nichipet EX II, 1–100 µL Nichiriyo, Japan). The time taken for complete penetration of the drops were measured using a stop watch, where the average times of 5 drops was taken as the WDPT for one replicate. The SWR was categorized into classes (both field and laboratory measurements) as wettable (WDPT ≤ 5 s), slightly repellent (5–60 s), strongly repellent (60–600 s), severely repellent (600–3600 s), and extremely repellent (WDPT > 3600 s) (Bisdom et al., 1993). Penetration times shorter than 0.5 s were considered as 0 s and the measurement of penetration time was terminated after 1 h.

The mini-disk infiltrometer (Decagon devices, Inc.), with a suction head of 1 cm, was used for this purpose. A leveled area of the field at a minimum distance of 2 m to the tree trunks were selected as the sampling points and the litter layer was carefully removed without disturbing the soil before the measurements. Before placing the The method proposed by Zhang (1997) was used to determine the k(–1 cm) of the tested soils (Lichner et al., 2007), which requires the measuring of cumulative infiltration with time and fitting the obtained results with the function:

$$I = C_1 t + C_2 \sqrt{t} \quad (1)$$

where the C_1 (m s^{-1}) and C_2 (m s$^{-1/2}$) parameters are respectively related to the k(–1 cm) and the S_W of the soil. The k(–1 cm) for the respective soil is then to be computed from:

$$k = C_1/A \quad (2)$$

where C_1 is the slope of the cumulative infiltration, I (cm) versus the square root of time ($t^{1/2}$) curve, and A relates the van Genuchten parameters of soil to the suction rate and the infiltrometer disk radius. The slope of the cumulative infiltration versus the square root of the time curve, and the k(–1 cm) were calculated based on the infiltration data gathered with the support of the Microsoft Excel spreadsheet published by Decagon (www.decagon.com/macro). The linear approximation of the relationship between cumulative infiltration and the square root of time (Eq. 3) was used to estimate the water sorptivity (S_W).

$$I = S_W \sqrt{t} \quad (3)$$

Data analysis

The laboratory and field experiments were conducted in triplicates and the results were statistically analyzed using linear regression and the analysis of variance (ANOVA) at a 5% level of significance ($p < 0.05$) using Microsoft Excel (2016) and STATISTICA software. The mean values of the measurements were reported, where the error bars in the figures indicate ± standard deviation.

RESULTS AND DISCUSSION

Figure 2 shows the potential (a, b, c) and actual field (d, e, f) SWR values as measured by the WDPT of the three plantation forest soils in both wet and dry seasons. Among the three plantation forests, CE soils showed the highest SWR in the dry season, whereas the EG soils showed the highest SWR in the wet season. In the wet season, all three forest soils showed a decrease in water repellency with increasing soil depth. In contrast, in the dry season, only CE soils showed a significant decrease in SWR with soil depth. Both EG and PC soils maintained high levels of repellency with decreasing soil depth down 15 cm in the soil profile. Both actual and potential SWR in all three tested layers of EG soils, (0–5, 5–10, 10–15 cm) showed extreme water-repellent conditions (WDPT > 3600 s). The two upper layers (0–5, 5–10 cm) of PC soils showed extreme (WDPT > 3600 s) while the 10–15 cm showed severe (WDPT > 2000 s) water-repellent conditions.

Low SWR in the wet season seems to correspond with the thickness of the litter layer on the surface of all the forest soils. In the wet season, the thickness of the litter layer was low, which was very high in the dry season. The temperature of all the locations is sufficient enough to maintain higher decomposition rates when there is enough water available. Although CE soils showed very high water repellency in the topsoil in the dry season. Interestingly water repellency dropped significantly with the depth. It means that the highly repellent compounds added to the topsoil are not moving downward irrespective of the sandy nature of the soils. Furthermore, very low organic matter content (~1–2%) in these soils can be considered another reason for low SWR levels in the lower levels of the profile. Conversely, the other two soils showed considerable high values of water repellency throughout the top 15 cm of the soil showing that the water repellent compounds transferred to the lower levels of the profile.

Unsaturated hydraulic conductivity, k(–cm), water sorptivity (S_W), contact angle, and water entry value (h_{we}) of the tested forest soils in both wet and dry seasons are presented in Table 2. It should be noted that infiltration did not initiate in the CE soils in the dry season, even with a 0.5 cm suction level in the mini-disk infiltrometer, and therefore, it was not possible to get the measurements for k(–1 cm) and S_W in CE soils for the dry season. An interesting finding in the EG and PC soils in the dry season was the presence of very high initial infiltration rates in some locations. These can be considered as an indicator for the presence of preferential flow paths. The h_{we} of water-repellent soils are in general known to be positive due to the requirement of high hydraulic pressure for the cessation of the SWR and force water into the soils (Karunarathna et al., 2010). In all three soils, the dry season with higher repellency (Figure 2) showed higher h_{we} compared with the wet season (Table 2).

The S_W is a measure of the ability of a soil to capture water rapidly that is considered as a key parameter governing the early stages of entry of water into the soil through infiltration (Shaver et al., 2003). Wallis et al. (1991) pointed out that the entry of water into soils may be retarded by even minor levels of repellency, indicating its hydrological significance. However, irrespective of the higher levels of repellency in the dry season, EU and PC soils did not show any significant difference in S_W for wet and dry seasons. Other than the wetting status of soils governed by the repellency, another potential reason for high rates of water absorption into soils in dry conditions is the differences in water potential of soils between dry and moist conditions. As the wetting of soil with water would theoretically be accelerated when the soil is in a drier condition, it might also be factored in, together with restriction for water movements caused by water-repellent effects, to the actual S_W of the soils. These contradictory influences can be considered as the reasons for soils to show no differences in S_W between dry and wet seasons.

Soils having water-repellent features are reported to resist or retard surface water infiltration (Doerr et al., 2000; Wahl et al., 2003). Our results are in line with some of the previous studies which report that water infiltration into hydrophobic soil is slower than into more hydrophilic soil (Letey et al., 1962). Relation of potential SWR, as measured by soil water contact angle, to the initial infiltration rate during the period of first 30 s is given in Figure 3. Initial infiltration rate showed moderate to strong negative linear correlation with soil-water contact angle in all three soils ($R^2 = 0.55$, 0.55, and 0.91, respectively in

Table 2. Unsaturated hydraulic conductivity (k), water sorptivity (S_W), contact angle, and water entry value (h_{we}) of the tested forest soils in wet and dry seasons.

	k(–1 cm) (cm h^{-1})		S_W (cm s$^{-1/2}$)		Contact angle (°)		h_{we} (cm)	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Eucalyptus								
Minimum	1.23	0.01	0.028	0.062	119	124	3.8	6.3
Maximum	6.97	4.45	0.130	0.133	78	110	3.3	4.0
Mean	2.46	1.83	0.082	0.080	103	115	3.6	4.9
S.D.	1.63	1.35	0.025	0.018	13	4	0.3	0.9
Pine								
Minimum	0.47	0.02	0.021	0.019	97	107	3.4	4.4
Maximum	2.89	5.86	0.168	0.164	67	69	1.3	1.4
Mean	2.33	2.11	0.148	0.143	83	83	2.4	2.8
S.D.	0.76	1.98	0.019	0.050	10	14	1.4	1.2
Casuarina								
Minimum	1.66	–	0.035	–	106	119	5.3	8.2
Maximum	44.83	–	0.259	–	85	104	3.8	5.4
Mean	23.39	–	0.127	–	100	111	4.8	6.8
S.D.	17.60	–	0.095	–	7	6	0.4	0.9

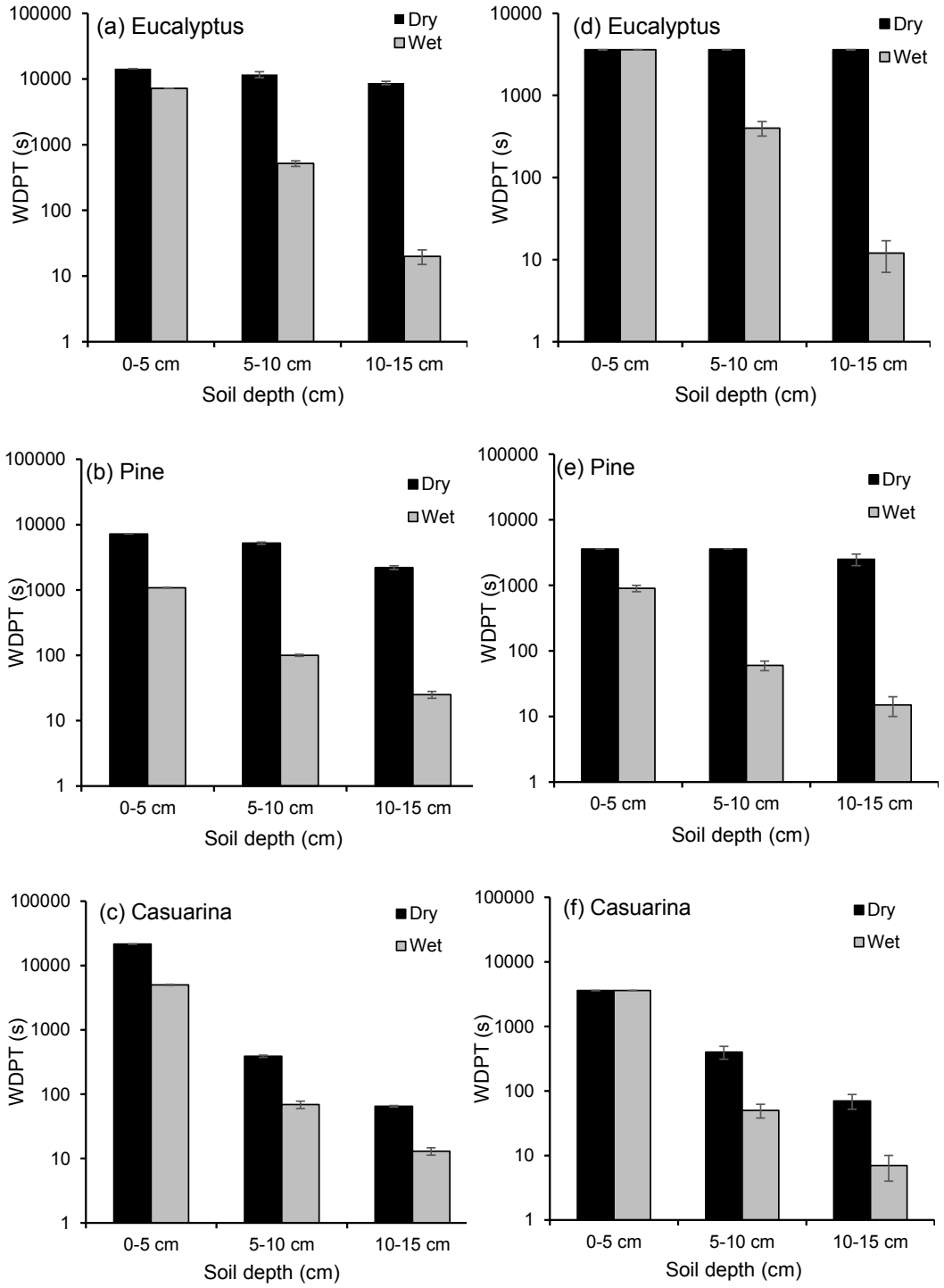


Fig. 2. Potential (a, b, c) and actual (d, e, f) soil water repellency as measured by water drop penetration time (WDPT) of Eucalyptus, Pine, and Casuarina plantation forest soils in both wet and dry seasons.

EU, PC, and CE soils). It was clear that the level of SWR decelerates water infiltration into all three soils at the initial level. The influence of SWR is reported to be more pronounced during the early stages of the infiltration process. (Letey et al., 1962; Lozano-Baez et al., 2020). This diminished water flow rate into soils can be considered as a result of increased flow resistance with increasing contact angle (Diamantopoulos and Durner, 2013).

Figure 4 shows the relation between the potential SWR as measured by soil-water contact angle and the $k(-1$ cm). Similar to the initial infiltration rate, $k(-1$ cm) in all the three forest soils decreased with increasing contact angle showing a negative exponential correlation ($R^2 = 0.34$, 0.37, and 0.44, respectively in EU, PC, and CE soils). The results on $k(-1$ cm) are comparable with Moody et al. (2009), who reported that hydraulic conductivity near saturation is inversely proportional to the SWR in fire-affected soils.

The relationship between $k(-1$ cm) and S_W, as obtained from the linear approximation of cumulative infiltration and the square root of the time, is presented in Figure 5. All three soils showed moderate to strong positive linear correlations between $k(-1$ cm) and S_W ($R^2 = 0.82$, 0.66, and 0.61, respectively in EU,

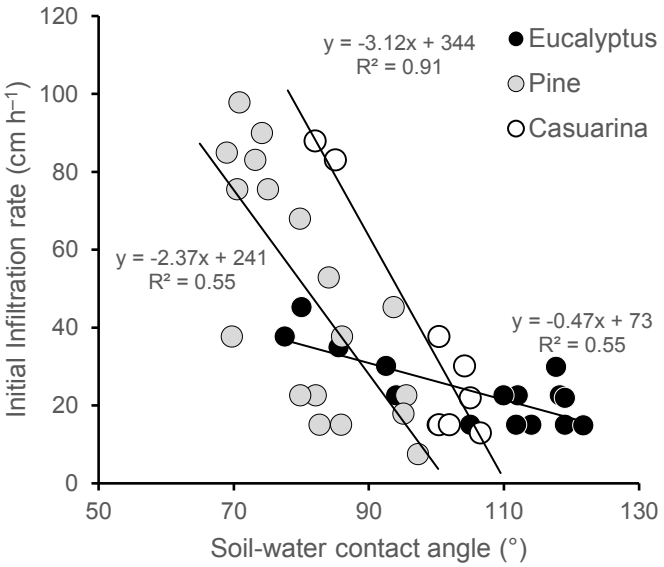


Fig. 3. Relation of Soil water repellency, as measured by soil water contact angle, to the initial infiltration rate during the period of first 30 s of infiltration in Eucalyptus, Pine, and Casuarina plantation forest soils.

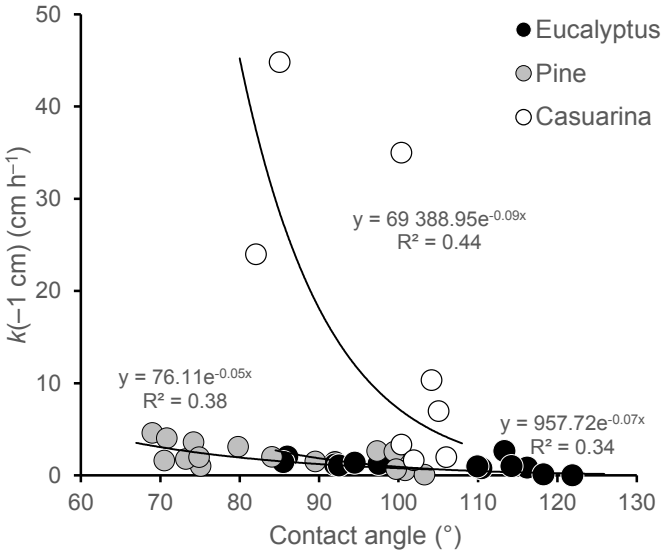


Fig. 4. Relationship between soil-water contact angle and the unsaturated hydraulic conductivity, k(–1 cm), in Eucalyptus, Pine, and Casuarina plantation forest soils.

PC, and CE soils), which were statistically significant at 0.05 probability level. It appeared that surface sorptivity is related to the subsurface unsaturated water flow in all three water-repellent soils.

The S_W is the ability of soil for the rapid capture of, or to uptake, water without any influence of gravitational effects (Philip, 1969). The h_{we} explains the critical pressure at the point of accomplishing instantaneous entry of water into soils. As both these parameters explain the entering of water into the soil at different conditions, S_W was plotted against h_{we} to observe the interrelation. The S_W showed a negative linear correlation (Figure 6) between h_{we} and S_W (R^2 = 0.70, 0.42, and 0.65, respectively in EU, PC, and CE soils), where the correlation between the two parameters for all three soils was statistically significant at 0.05 probability level. The result shows that the surface water absorption related to the critical surface water entry pressure that force water into the soil.

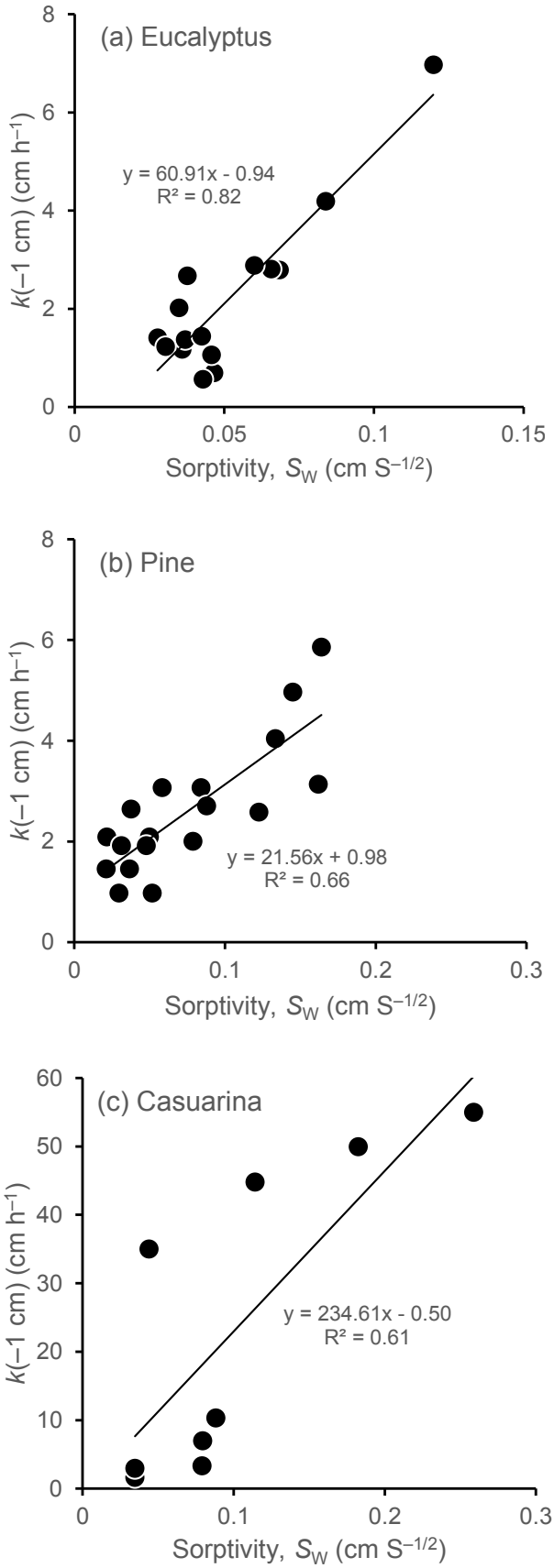


Fig. 5. Relationship between unsaturated hydraulic conductivity, k(–1 cm), and water sorptivity, S_W , in (a) Eucalyptus, (b) Pine, and (c) Casuarina plantation forest soils.

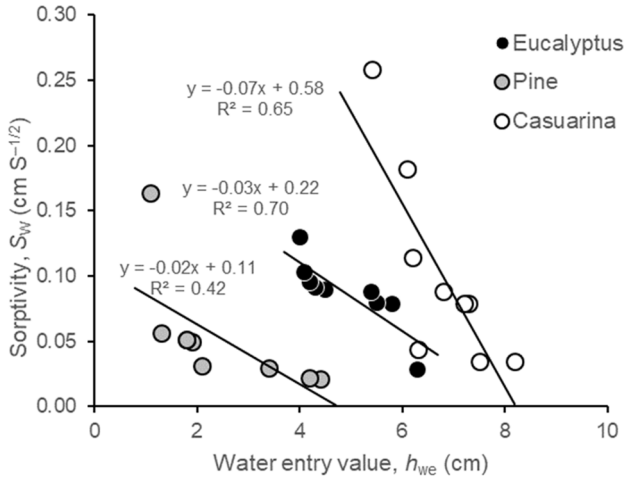


Fig. 6. Relationship between water entry value (h_{we}) and water sorptivity (S_W) in Eucalyptus, Pine, and Casuarina plantation forest soils.

CONCLUSIONS

All three plantation forest soils showed clear differences in repellency between wet and dry seasons. The dry season showed higher repellency that seems to correspond to the thickness of the litter layer on the surface. Positive linear correlations between k(–1 cm) and S_W, and negative linear correlations between S_W and h_{we}, confirmed that the surface water absorption is related to both subsurface unsaturated water flow and surface water entry pressure.

Water entry into soils as well as the subsurface water flow was hindered by the SWR. For the initiation of water to infiltrate into the soil under natural conditions, the ponding depth of water on the soil surface should be equal to or exceed the water entry value. High water entry values in the dry season predict high potentials for intensified surface runoff and topsoil erosion in the dry season. Considering the localized points with very high infiltration rates, presence of preferential flow paths can be suggested as the possible mode of water entry into soils in rainfall events after strong dry spells. Future research will be required on the interactions between soil biology and soil properties such as pore structure that would influence water flow into and within soils, and the potential runoff levels.

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