Water repellency in eucalyptus and pine plantation forest soils and its relation to groundwater levels estimated with multi-temporal modeling

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Abstract: Water repellency makes soils capable of resisting to the penetration of water applied on the surface and inflict various influences on groundwater. The objectives of the present study were to identify the water repellency under pine and eucalyptus plantations, to determine social impacts of water level changes, to find possible changes in groundwater levels in the surrounding areas during the past four decades, and to relate water repellent characteristics of soils with the groundwater level changes. The study was conducted in eucalyptus (*Eucalyptus grandis*) and pine (*Pinus caribaea*) plantation forests located in Upcountry intermediate zone, Sri Lanka. Each land was separated into three blocks (B1, B2, B3) based on the slope. Water repellency was measured with water drop penetration time (WDPT) and contact angle. The water entry value was estimated with the pressure head method. Interconnected social impacts was examined using a questionnaire based survey. Groundwater levels from 1980 to present were modeled with remotely sensed information. Both eucalyptus and pine forest soils showed water repellency, which decreased with increasing soil depth. Eucalyptus soils showed highly hydrophobic conditions on the surface (WDPT>7200 s). Ponding depths required for entry of water into the soil in eucalyptus soils was 4.6–5.3 cm, whereas that of pine soils was 1.5–4.0 cm, although achieving these levels would be difficult considering the steep slopes. Contact angle showed positive logarithmic correlation with water entry value. The people living in the surrounding areas expressed less water availability for their domestic purposes, decreased water level in household wells, and drying up of natural water resources at present compared with 1980s. Modelling with remotely sensed thematic maps confirmed that the groundwater levels in both areas has decreased over the time. It indicated that the eucalyptus and pine vegetation have created unfavorable conditions in regard with water entry and groundwater recharge. Proper attention from the responsible authorities will be essential to prevent the adverse impacts of on groundwater resources.

Keywords: *Eucalyptus grandis*; Groundwater modeling; *Pinus caribaea*; Water repellency; Water entry value.

INTRODUCTION

Soil water repellency (SWR) is a phenomenon that make soils capable of resisting to the penetration of water applied on the surface. It is caused by organic compounds containing hydrophobic properties that are coating individual soil particles, or present in soil as interstitial matter. These hydrophobic molecules are released at natural conditions, during fires from plants, organisms, and decomposing organic matter in soils. Water repellent coatings also can restrict the interactions between pores inside and outside of the soil aggregates (Fér et al., 2016). SWR lessens the affinity of soils towards water to different degrees, resisting the wetting for durations that may range from a few seconds to hours or days (Doerr and Thomas, 2000). It influences important hydrological and geomorphological consequences such as lowered infiltration rates, upsurge of the overland flow, uneven wetting, development of preferential fingerlike and bypass flows (Imeson et al., 1992; Kobayashi and Shimizu, 2007). SWR decreases the capacity of infiltration in soil and enhances runoff events specially in steep slope lands during the early stages of rainfall (Contreras et al., 2008; Siteur et al., 2016). In addition, organic-clay coatings on soil aggregates in some soils may influence water and solute transport into soil aggregates (Fér and Kodešová, 2012; Gerke and Köhne, 2002).

Occurrence of SWR has been reported in diverse natural climatic and weather conditions, soil types and vegetation cover of large trees to small turf grasses. Forests with water repellent conditions have been recognized to alter the hydraulic properties of soils (Kajiura et al., 2012; Kobayashi and Shimizu, 2007; Leelamanie and Nishiwaki, 2019; Lichner et al., 2013; Wahl et al., 2003). Various kinds of impacts of SWR on the soil water systems have been characterized by several studies under different land uses, climatic conditions, and regions. Water repellency is frequently found in soils covered by tree species such as Eucalyptus (Eucalyptus globulus), Cluster pine (*Pinus pinaster*), Scots pine (*Pinus sylvestris*), Cypress (*Chamaecyparis obtusa*), Japanese cedar (*Cryptomeria japonica*), and Casuarina (*Casuarina equisetifoli*a) (Alagna et al., 2017; Benito et al., 2019; Iovino et al., 2018; Kobayashi and Shimizu, 2007; Leelamanie, 2016; Leelamanie and Nishiwaki, 2019; Lichner et al., 2013). The SWR observed in conifer forests is considered to be a natural characteristic rather than being induced by external factors such as forest fires (Doerr et al., 2009). Water repellency is known to influence groundwater in different ways. It induces preferential flow paths that provide shortened and faster routes for the transport of water and solutes, accelerating the driving of solutes to the groundwater increasing the risk of groundwater pollution (Bauters et al., 1998; Ziogas et al., 2005). Eucalyptus and pine plantations in Sri Lanka, which show water repellent conditions (Leelamanie et al., 2016), are getting increasing attention at present due to the social uneasiness on lowering the availability of water resources related to the establishment of these exotic species.

Groundwater is one of the most important natural resources on the earth that supports the ecological diversity and human health (Rao et al., 2001). Falling of groundwater tables are reported at remarkable rates in most parts of the world (Giordano, 2009). Decline of groundwater level causes numerous eco-environmental problems such as oasis degeneration, drying up of wetlands, disappearance of streams and artesian wells, and salt water intrusions etc. The recharge of groundwater depends mainly on several factors such as infiltration capacity and permeability, stochastic characteristics of rainfall, and other climatic factors. In arid regions, recharge of groundwater occurs mainly through ephemeral streams. In semiarid regions, the recharge of groundwater is mostly irregular and occurs in the periods of heavy rainfall (Şen, 2015). With above 1800 mm of average annual rainfall (Zubair and Ropelewski, 2006) the main natural groundwater recharge in Sri Lanka is by the precipitation as rainfall. In general, upland areas are considered to be the sources for groundwater recharge or replenishment, and lowland areas are considered to be the points of discharge. In recent decades, the natural systems of groundwater recharge and discharge in many regions of the world are found to be critically altered by various human activities (Giordano, 2009). Groundwater table diminishes when the rate of recharge is lower than the rate of withdrawal (Senanayake et al., 2016). It is clear that low rates of replenishment or high rates of withdrawal may lead to depletion of groundwater table, leading to dropped water level in groundwater wells as well as in surface water resources such as lakes and streams.

Remote sensing and Geographical Information System (GIS) play an important role in the management of water and land resources. GIS technique can be used as an efficient tool in identification of groundwater levels in different locations. Remote sensing can be effectively used to acquire surface feature information related to groundwater such as land use, land forms, and drainage and to handle widespread data for modeling (Brunner et al., 2007). Standardizing the low reflectance in red band and higher reflectance in infrared band, it is possible to measure various vegetation-related features using normalized difference vegetation index (NDVI) (Pan et al., 2008). Modelling techniques use remotely sensed data with surface reflectance to relate surface soil moisture to the shallow groundwater level. The relationship of the surface reflectance and the depth to the groundwater level can be assessed with the observation of groundwater wells (Pan et al., 2008).

Only limited reports are available to understand the influence of repellency-induced changes to the groundwater levels. Adane et al. (2017) recently reported that the presence of water repellent conditions reduced groundwater recharge, which is caused by the combinations of increased extraction of water by plants and the declined infiltration rates due to water repellent surface layer. Still, the hydrological alterations caused by soil water repellent conditions and their multi-temporal consequences on groundwater dynamics have received comparatively a less attention. Present study was planned with the four main purposes: to identify the SWR under pine and eucalyptus plantations; to determine the social impacts of water level changes using a questionnaire based survey; to find the possible changes in groundwater levels in the surrounding areas of pine and eucalyptus plantations during the past four decades; and to relate the water repellent characteristics of the soils with the groundwater level changes of the areas.

MATERIALS AND METHODS
Study sites and soil sampling

The experimental site one (S1) was a eucalyptus (*Eucalyptus grandis*) plantation forest in Diyathalawa with an area of around 100 ha, located in the Upcountry intermediate zone (IU3c agro ecological region) of Sri Lanka (National Atlas of Sri Lanka, 2007). The mean annual rainfall is above 1700 mm. The second experimental site (S2) was a pine (*Pinus caribaea*) plantation forest in Haputale with an area of around 5 ha, which was also located in the Upcountry intermediate zone. The area belongs to the IU3a and IU3b agro ecological regions with annual precipitation of 1700–1900 mm. The road distance between the two study sites is around 11 km (the areal distance ~5–6 km). In the both sites, the largest rainfall events are in between December to February and the mean annual temperature is in the range of 20–22.5°C. The soils of the two sites are of a sandy loam texture and classified as red yellow podzolic soils under local classification and Hapludults under USDA classification (Soil Survey Staff, 2014).

Three sampling blocks (B1, B2, and B3) were selected from each site based on the slope of the experimental site, where B3 was selected to be on the top of the hill in both sites. The distances between the blocks were kept around 100–150 m. Table 1 shows the coordinates of the three soil blocks and slopes of the two sites. Core samples (undisturbed: for measurement of bulk density) and the bulk samples (disturbed) were collected from the blocks at the depths of 0–5, 5–10, and 10–15 cm in three replicates for each depth, in years of 2017 and 2018, in wet season (November to February). The collected samples were transported to the laboratory in labeled and sealed polythene containers.

Table 1. Sampling locations and land slopes in eucalyptus and pine plantation forests.

Soil Block	N	E	Slope (°)
Eucalyptus			
B1	06° 47' 42"	080° 57' 57"	10.4
B2	06° 47' 45"	080° 57' 58"	20.3
B3	06° 47' 56"	080° 57' 43"	34.4
Pine			
B1	06°46'15"	080°55'50"	11.4
B2	06°46'13"	080°55'52"	24.8
B3	06°46'13"	080°55'50"	41.5

Laboratory measurements

The samples were air dried at room temperature (27±3°C), and 75±5% relative humidity, for 3 days. Samples were passed through a 2 mm mesh to eliminate the coarse particles before the soil testing. The persistence and the degree of water repellency was measured using the water drop penetration time (WDPT) and soil-water contact angle, respectively. The critical point of water-entry into the soil was measured using the water entry value (Wang et al., 2000) of the samples. Bulk density (Undisturbed core method; Blake and Hartge, 1986a), particle density (Pycnometer method; Blake and Hartge, 1986b), Porosity (numerical method), Texture (Hydrometer method; Bouyoucos, 1962) and OM% (Loss on ignition method; Schumacher, 2002) were determined all soil depths for both sites. The measurements were conducted in in three replicates, in the laboratory with air-dried samples.

The WDPT test

Soil samples were placed in porcelain containers with a sample thickness of >5 mm to avoid interferences of drops reaching the bottom of the containers. A burette was filled with distilled water and one drop (50±1μl) of distilled water was carefully placed on the soil surface from a height of about 10 mm to minimize the collision impacts by the falling drops. The volume of the droplet was set to 50 μl to represent the average size of a raindrop. Containers were covered with lids to minimize the evaporation during the experimental period. The time taken for water drop to complete the penetration was measured using a stop watch (Leelamanie et al., 2008). Penetration 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 7200 s and all WDPTs exceeding 7200s were assigned to be 7200 s. The WDPT values were determined in six replicates for each soil depth in the three blocks in both sites.

Soil-water contact angle

The Soil-water contact angle was measured using the modified sessile drop method (SDM) (Bachmann et al., 2000), in six replicates, using a digital microscopic camera (FS-3100-PC, Fujikoden Co. Ltd., Japan). Monolayers of soil samples was prepared by sprinkling the air dried and sieved soil samples on a double-sided adhesive tape (1.5 cm × 1.5 cm) fixed on smooth glass slides. Sprinkled soil was pressed to the tape using a 100 g weight for 10 s and the surplus soil was removed by gently tapping the glass slide. To ensure the stabilization of a soil monolayer on the adhesive tape, the same procedure was repeated twice. The slides with soil monolayers were placed on the stage of the digital microscopic camera. A drop of distilled water (10 μL) was placed on the soil surface using a micro pipette (Nichipet EX II J15615241. Nichiriyo, Japan). Digital micro-photograph of the horizontal view of the water drop was taken within 1 s. Contact angle of each sample was determined using the micro-photographs of the horizontal view of the drop on the soil monolayer (Leelamanie et al., 2008; Leelamanie, 2016), using the both points of contacts of the water to the soil layer in the two-dimensional photograph of the drop.

Water entry value

Low hydraulic pressures at the soil surface is not sufficient to make water infiltrate into water repellent soils. The critical pressure head that requires to the breakdown repellency and start the infiltration can be determined using the water entry value. The water entry values of the samples were tested for soils collected from the surface (0–5 cm) using the pressure head method (Wang et al., 2000). Air-dried 50-g soil samples were placed on the porous plate of a Buchner funnel, which was covered with a membrane filter mounted filter paper, and the funnel was connected to a burette by a flexible tube. A hydraulic pressure was applied to the soil by raising the burette level, starting from a negative pressure head to avoid initial wetting of the soil (Wang et al., 2000). The pressure was carefully increased by 5 min time intervals up to the point where the water enters the soil matrix. At the point of water entry, the height of the water column was measured with respect to the reference level considering the soil as the water entry values of the samples (Liyanage and Leelamanie, 2016).

Groundwater modeling with remotely sensed information

This method was used to determine the relations of the irregularities in recharge of groundwater in water repellent soils to the groundwater levels of the areas surrounding the study sites. The method depends on the fact that the soil moisture on the surface is related with the shallow groundwater level. As the reflectance of the land surface related to normalized difference vegetation index (NDVI) obtained from the remote sensing images varies with the surface soil moisture, a relationship between the reflectance obtained from the remote sensing images and groundwater level depth using the method by Pan et al. (2008).

The NDVI is related to the surface vegetation coverage, in regard with the quality or the density. The higher the density of vegetation, the larger the value of NDVI.

$$NDVI = (Rs_2 - Rs_1)/(Rs_2 + Rs_1) \tag{1}$$

where Rs_1 and Rs_2 are respectively the radiance of the band 1 (near infrared) and band 2 (red) in Landsat images (wave lengths: 0.63–0.67 μm and 0.77–0.90 μm for band 1 and 2 respectively). The temperature surface can be determined using the split window technique with thermal infrared band data.

$$T_S = Rs_{10} + a(Rs_{10} - Rs_{11}) + c \tag{2}$$

T_S denotes the surface temperature (Land surface temperature, LST), Rs_{10}, Rs_{11} are the radiance of thermal bands 10 and 11, respectively in Landsat images (wavelengths: 10.6–11.19 μm and 11.5–12.51 μm for band 10 and 11, respectively), a denotes the model parameter, and c denotes the split window coefficient. The soil moisture on the surface is described by using the LST and NDVI.

$$MC_S = f(T_S, NDVI) \tag{3}$$

where MC_S is surface soil moisture content.

The depth level of shallow groundwater is related to the surface soil moisture, where the relationship between the groundwater level depth and the soil moisture is stated as follows

$$MC_S = \alpha_0 + C_1 \exp(D_W) \tag{4}$$

D_W is the depth of groundwater level. By combining Eq. (3) and (4), a mathematical model can be developed for the depth of groundwater level (Pan et al., 2008);

$$D_W = k \times \ln(NDVI \times T_S) + b \tag{5}$$

where k and b are the coefficients that can be achieved by curve fitting using the groundwater levels obtained by the observation of water levels of groundwater wells in the field. The field data on the water levels of groundwater wells situated surrounding both study areas (3 wells per study area) were gathered for consecutive period of six months to represent (Pan et al., 2008). The *NDVI* and T_S parameters were estimated through remote sensing images of the areas in same time period. Surface temperature and NDVI thematic maps for eucalyptus and pine plantation forest areas in 2018 are presented in Fig. 1 and Fig. 2. Then the D_W values were plotted against the ln(*NDVI* × T_S) to obtain a linear correlations and the k and b values were determined for the linear curves. Finally, these k and b coefficients can be used in the Eq. (5) with *NDVI* and T_S parameters estimated through remote sensing images in the areas in the
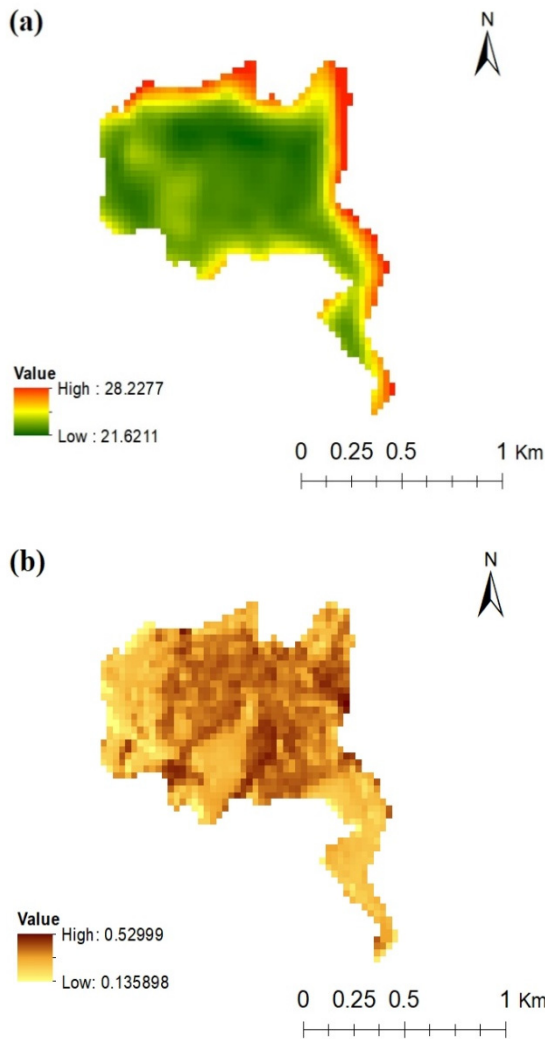
Fig. 1. Thematic maps of the land surface temperature (LST) and normalized difference vegetation index (NDVI) for eucalyptus plantation forest area in 2018.

Fig. 2. Thematic maps of the land surface temperature (LST) and normalized difference vegetation index (NDVI) for pine plantation forest area in 2018.

past. These estimated k and b values were used with *NDVI* and T_S parameter for the years of 1980, 1990, 2000, 2010 and 2018, to estimate depth to the groundwater level from surface in both Haputale (pine) and Diyathalawa (eucalyptus) areas.

Remote sensing mages were obtained from satellite sensors for 1980 (Landsat 5), 1990 (Landsat 5), 2000 (Landsat 7), 2010 (Landsat 7), and 2018 (Landsat 8). Pre-processing functions were performed for the satellite images before analyzing. Google earth application was used to extract the maps of the study areas (eucalyptus and pine plantation forests). These maps were used to subset the study areas from Landsat images. Thermal bands of the Landsat images were used to estimate the LST and NDVI through the raster image calculator in ArcMap tool (ESRI, 2017).

Social impacts of SWR

Questionnaire based survey was conducted in Haputale and Diyathalawa areas to relate onsite SWR of the studied sites to the hydrological consequences and interconnected social impacts. Forty persons from each area were selected randomly among the people living near (within a distance of 5km to each site) to the respective pine and eucalyptus plantations for this
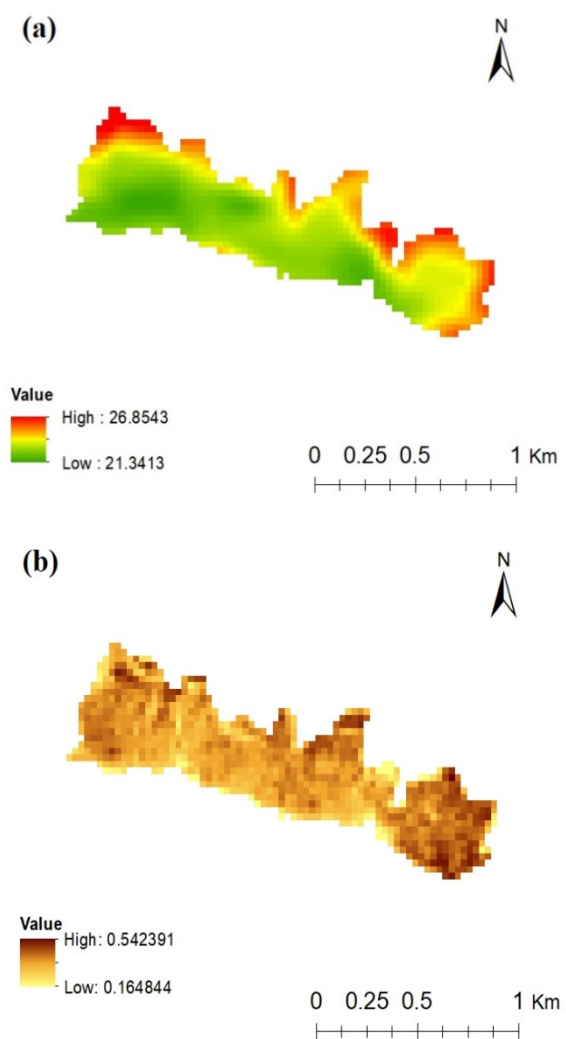
survey. Questions were mainly focused to determine the impressions and opinion of the people in relation to the hydrological consequences, basically the water scarcity conditions comparing the past and present conditions. For the statistical analysis, the responses of people on the availability of water for their domestic purposes were separated into three categories as 'better', 'worse', and 'no change' and assigned 2, –2, and 0, respectively. The responses on the changes in water level in their household groundwater wells were also separated into three categories as 'increase', 'decrease', and 'no change' and assigned 2, –2, and 0, respectively. The responses of the people living in the Diyathalawa and Haputale areas on the drying up of proximate artesian wells and water resources were separated into two categories as 'yes' and 'no'.

Data analysis

The data were statistically analyzed with analysis of variance (ANOVA), regression analysis and correlation, at 0.05 probability level using Microsoft Excel 2013 data analysis tool pack. Results from questionnaire based survey was analyzed using non-parametric statistics with Wilcoxon sign rank test, where Minitab 17 software was used for the analysis.

RESULTS AND DISCUSSION
Basic properties of soils

Both soils showed comparatively high bulk densities (mostly > 1 g cm^{-3}). The texture of soils in both sites in all the soil depths were sandy loam. Organic matter decreased with increasing depth of the soil profile in all three blocks in both study sites. Table 2 presents the information on the basic properties of the soils in the two study sites (three blocks, three depths) in detail.

Presence of water repellency

The persistence of water repellency in eucalyptus and pine plantation forest soils as measured by WDPT (log WDPT) is given in Fig. 3. In all the soil, the highest WDPT was found in the top soil layer (0–5 cm), decreased with the increasing soil depth. Surface soils in all three blocks of the eucalyptus forest were extremely water repellent with WDPT exceeding 7200 s (Fig. 3a). Pine forest soils showed lower repellency compared with that of eucalyptus except in the B3, which showed WDPT> 7200 (Fig. 3b). Surface soils in B1 showed slight water repellency (10 s <WDPT< 60 s) and those of B2 showed severe water repellency (600 s <WDPT< 3600 s).

The degree of water repellency in eucalyptus and pine plantation forest soils as measured by soil-water contact angle is given in Fig. 4. Similar to the WDPT results, surface soils of both eucalyptus and pine forests showed the highest contact angle and decreased with increasing soil depth. Eucalyptus forest soils showed highly hydrophobic nature on the surface with soil-water contact angles in all the blocks exceeding 90° (Fig. 4a). Pine forest soils showed comparatively low contact angles (83–84°) on the surface in B1 and B2, and similar to the WDPT results, very high contact angle in B3 (100°) (Fig. 4b).

Several contradictory reports are available to show the water repellency to be existing from the top down to the weathered horizon as well as to be increased with increasing soil depth (eg. Doerr et al., 1996; Santos et al., 2016). However, weakening of water repellency with increasing soil depth is more commonly reported in casuarina, pine, eucalyptus, and oak forest soils in most continents (Badia-Villas et al., 2014; Flores-Mangual et al., 2013; Leelamanie, 2016; Lichner et al., 2007; Rodrıguez-Alleres et al., 2007). It was clear that the highest repellency of both eucalyptus and pine soils tested in this study
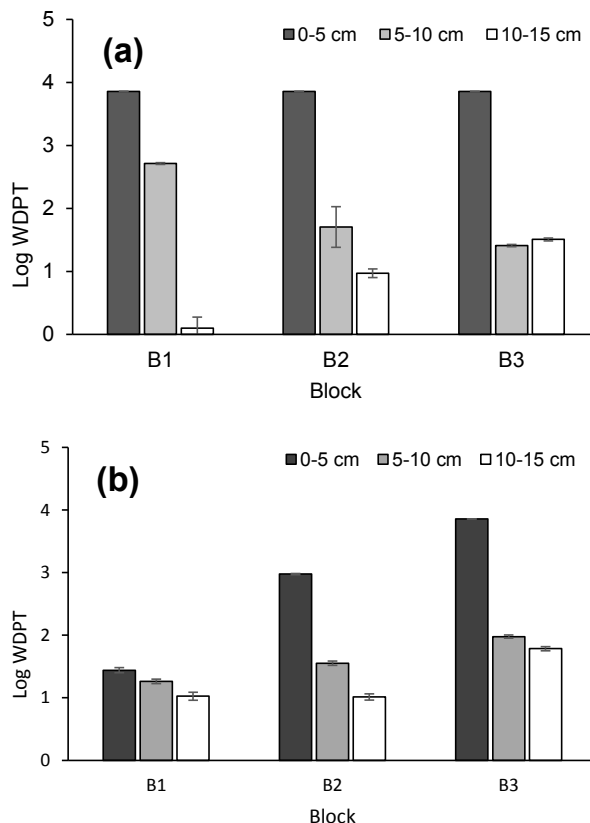

Fig. 3. The persistence of water repellency in eucalyptus and pine plantation forest soils as measured by WDPT (log WDPT).

confined to the surface layer revealing a diminishing water repellency with increasing depth of soil. According to numerous reports, soil water repellency is influenced by the content and the composition of organic matter. Mostly reported correlations between the organic matter content and SWR are positive, where the reductions in the SWR soil depth are generally attributed to the diminishing organic matter content (McKissock et al., 1998; Rodrıguez-Alleres et al., 2007; Vogelmann et al., 2010; Wallis et al., 1990; Woche et al., 2005). Accordingly, the lowering of SWR towards deeper soil layers in the present study can be considered related to the declining of organic matter content.

Table 2. The basic properties of eucalyptus and pine plantation forest soils.

| Soil property	Block 01			Block 02			Block 03		
	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
Eucalyptus									
Bulk density (g cm^{-3})	1.03 ±0.10	1.11 ±0.04	1.20 ±0.01	0.98 ±0.08	1.04 ±0.11	1.19 ±0.08	1.02 ±0.06	1.04 ±0.09	1.04 ±0.04
Porosity (%)	53.5 ±7.1	50.1±4.6	48.8±2.9	57.37±6.5	58.6±2.3	51.3±5.4	57.0±2.7	55.5±5.7	55.0±3.6
Sand %	80.3 ±1.5	74.4 ±0.1	79.5 ±0.1	82.1 ±0.1	79.4 ±0.1	76.7 ±0.2	79.4±0	71.6 ±0.1	81.9 ±0.1
Silt %	6.9±1.5	6.8±1.5	4.3±1.5	5.1±0	6.9±1.5	10.3 ±0.1	3.4±1.5	7.7±0	2.6±0
Clay %	12.9±0	18.8 ±1.4	16.2 ±1.4	12.8±0	13.7 ±1.5	12.9 ±0.1	17.1 ±1.5	20.6 ±0.1	15.5±0
Organic matter (%)	9.93 ±0.12	7.04 ±0.05	6.88 ±0.04	11.6 ±0.30	7.71 ±0.08	6.33 ±0.02	9.19 ±0.17	7.83 ±0.12	6.75 ±0.03
Pine									
Bulk density (g cm^{-3})	0.93±0.05	1.03±0.08	1.03±0.18	0.82±0.01	1.04±0.08	1.11±0.09	1.13±0.07	1.15±0.06	1.22±0.05
Porosity (%)	63.4±0.9	59.6±2.8	60.5±6.2	67.6±0.6	60.9±1.0	58.7±4.6	56.5±4.4	59.5±1.0	51.1±2.2
Sand %	76.12±7.32	74.17±4.16	73.84±1.57	69.16±2.26	69.89±2.73	72.88±3.51	75.76±2.90	73.62±1.32	71.11±1.58
Silt %	9.76±6.21	7.37±5.74	9.02±1.56	10.6±2.86	7.07±1.45	7.89±0.14	10.79±2.80	10.02±1.63	10.82±2.64
Clay %	14.12±1.66	18.46±1.63	17.14±1.57	20.23±1.31	23.03±1.32	23.53±10.92	13.46±2.67	16.37±2.60	18.07±3.24
Organic matter (%)	19.08±1.6	15.47±1.11	12.4±0.39	16.12±1.1	11.81±2.99	10.4±0.8	11.09±0.38	10.03±0.29	9.12±0.42
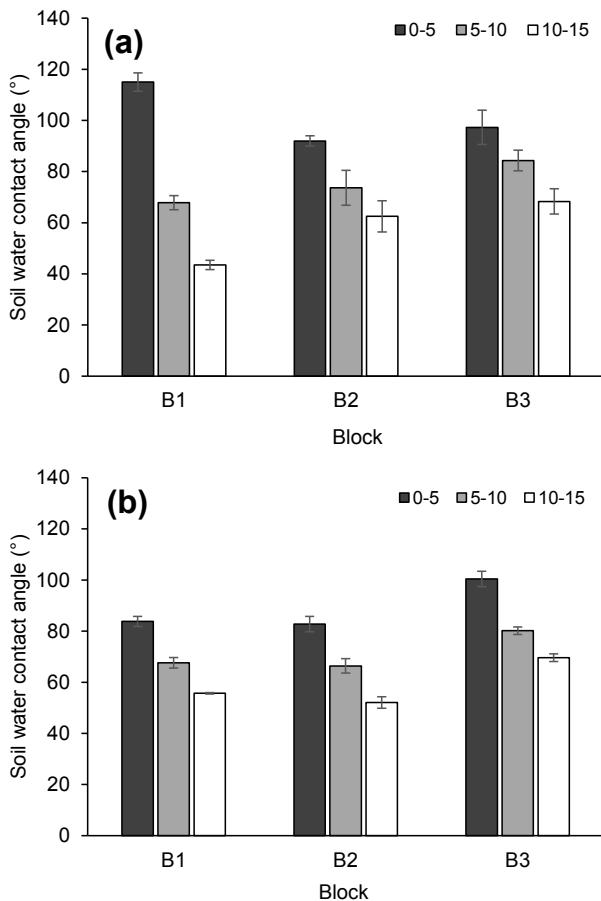
Fig. 4. The degree of water repellency in eucalyptus and pine plantation forest soils as measured by soil-water contact angle.

Water entry value

Fig. 5 presents the water entry values of the eucalyptus and pine forest soils. The water entry values of eucalyptus forest soils showed significantly high values than those of pine forest, except in B3 soils. It was clear that the water entry values of all the soils can be closely related to the water repellent conditions on the surface soils. As presented in Fig. 6, soil-water contact angle showed positive logarithmic correlation ($R^2 = 0.66$) to the water entry values. Liyanage and Leelamanie (2016) observed similar results in soils treated with hydrophobic casuarina leaf litter. Lee et al. (2015) observed similar results, and reported that water entry pressure increased with increasing water repellency in an artificially-prepared water-repellent silty soil. The increasing hydrophobicity of soil tend to increase the air encapsulation within the soil during the intake of water, which is known to reduce the rates of water intake by increasing the pressure required for the water entry of the repellent soils (Liyanage and Leelamanie, 2016; Sullivan, 1990). As explained by Letey et al. (2000), the water entry pressure is a function of both soil-water contact angle and the pore radius. Theoretically, a need of positive pressure arises to force water entry into the soil when the soil-water contact angles exceed 90°. This justifies the positive correlation between the water entry values and the soil-water contact angle (Bauters et al., 2000). With positive water entry values in water repellent soils, a ponding depth would be required to induce water entry into soils (Letey, 2001; Wang et al., 2000). High water entry values predict the potential risks of soil erosion, where building up of required ponding depths for water intake is difficult due to various reasons such
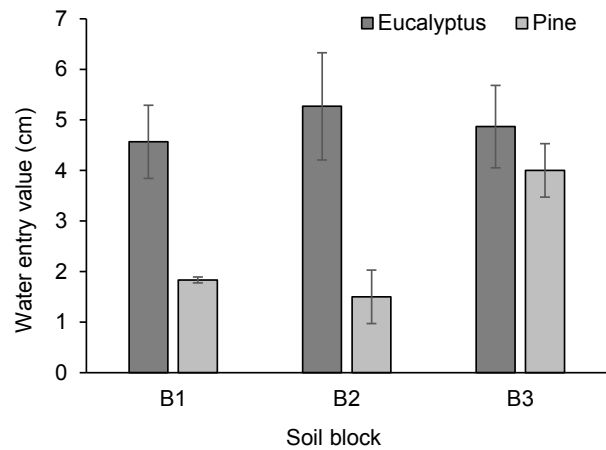

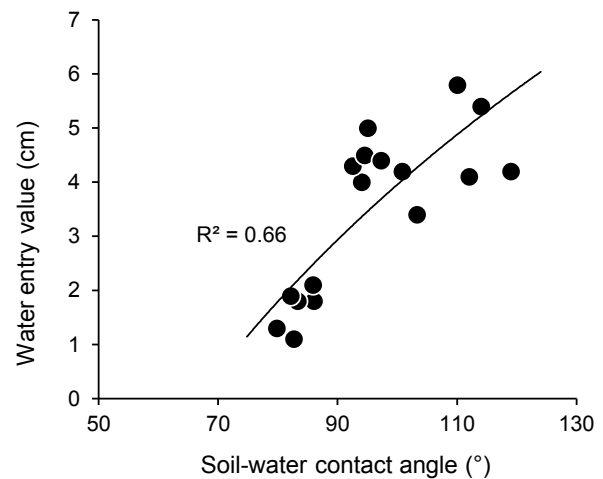Fig. 5. Water entry values of the eucalyptus and pine forest soils.

Fig. 6. Relation of soil-water contact angle to the water entry values of the eucalyptus and pine forest soils.

as high steepness of the slopes, which is characteristic in the study-sites of the present research.

Social impacts as revealed by questionnaire based survey

The responses of the people living in the surrounding areas of the two plantation forests on the availability of water for their domestic purposes, changes in water level in their household wells, and experience in drying up of artesian wells and water resources at present condition when compared with the situation in 1980–1990 are presented in Fig. 7. Results showed that about 90% the selected people living in both Diyathalawa and Haputale areas neighboring the eucalyptus and pine plantation forests, expressed that availability of water for domestic purposes at present is poor (response: 'worse') compared with the situation in 1990 (Fig.7a), and 10% expressed no difference (response: 'no change') in the availability of water. Considering the response of the people, Wilcoxon sign rank test revealed a statistically significant ($p < 0.05$) level of water scarcity conditions compared to the past in both areas.

About 85% of the interviewed people in Diyathalawa area (neighboring eucalyptus forest) and 88% in Haputale area (neighboring pine forest), claimed that they have experienced decreases in water levels in their groundwater wells compared with the past (Fig. 7b). Wilcoxon sign rank test revealed
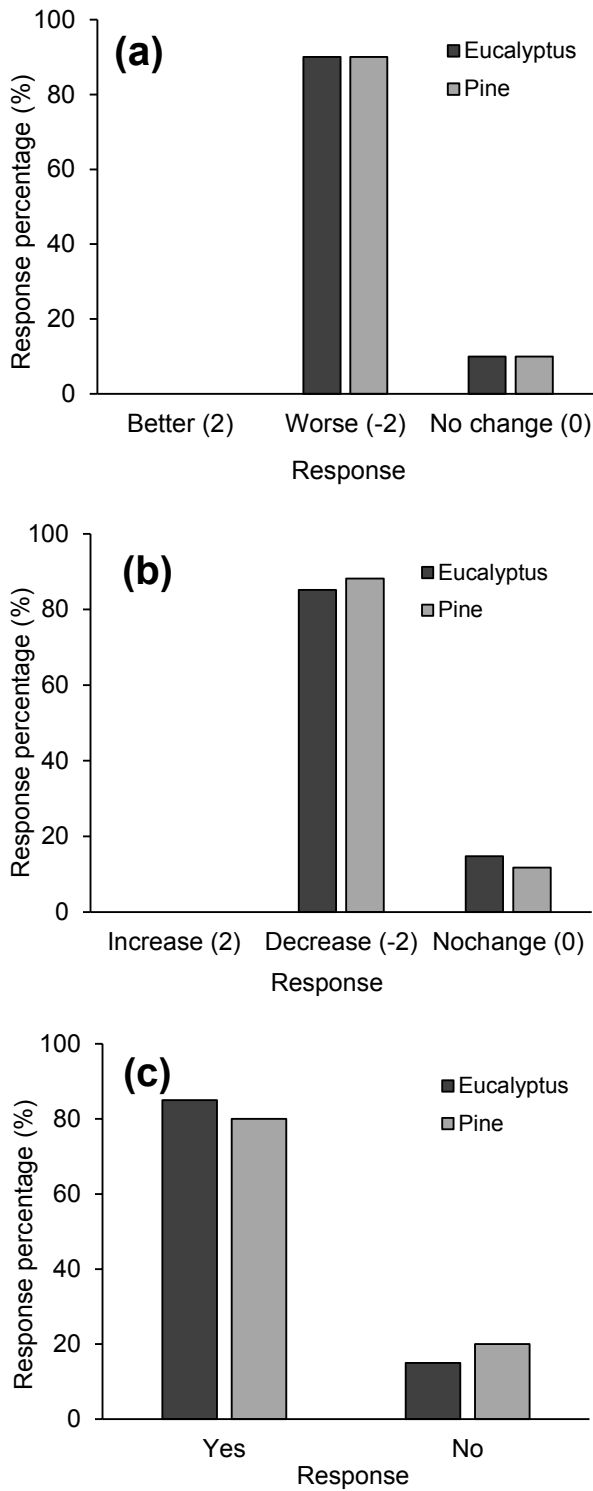
Results of the questionnaire based survey revealed that the people living in the surrounding areas of eucalyptus and pine forests have experiences in lowering groundwater levels and water scarcity conditions compared with the past. The groundwater level and natural water resources are highly important parameters for the people living in both areas as the people are accustomed to the use of groundwater wells as well as artesian wells and other natural water resources for their domestic purposes. The survey further revealed that the majority of the people are considering the introducing of these exotic species as the cause of initiating the water scarcity conditions. However, no person living in the area had any knowledge on water repellent conditions. People believed that the deep root systems in these exotic species withdraw water from deeper layers resulting in water scarcity conditions.

Groundwater levels through modeling

Changes in depth to the groundwater level from the surface in Diyathalawa and Haputale areas, respectively related with eucalyptus and pine plantation forests, from 1980 to 2018 as estimated through modelling using LST and NDVI thematic maps are presented in Fig. 8. The depth to the water level in groundwater wells in both Diyathalawa and Haputale areas showed exponential increases during the period from 1980 to 2018, revealing a gradual decrease in the groundwater levels. The standard deviations of the curves for eucalyptus was 1.227 (m) and that of pine was 1.356 (m).
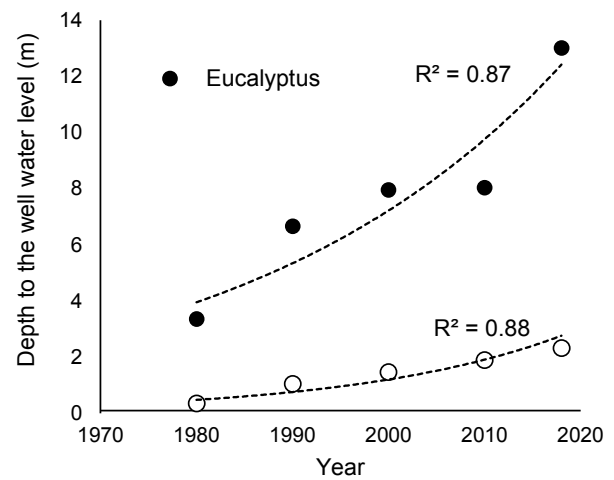

Fig. 8. Changes in depth to the groundwater level from the surface in Haputale and Diyathalawa areas from 1980 to 2018.

The reduction of groundwater level was apparently low in the Haputhale area, where the pine plantation is located, compared to the Diyathalawa area where eucalyptus plantation is located. In addition, dense and extremely water-repellent litter cover under these plantations might play an important role in assisting the overland flow, reducing the groundwater recharge. The results further revealed that the changes in groundwater level were very low in 1980s. The exponential trend of lowering the groundwater table hints on more pronounced water scarcity conditions in the future. The results of the present study revealed lowered water movements in the soil matrix as well as uneven distribution of water in the profile related to extreme water-repellent conditions observed on the soil surfaces of both pine and eucalyptus plantation forest soils.

Fig. 7. The responses of the people living in the surrounding areas of the two plantation forests on (a) the availability of water for their domestic purposes, (b) changes in water level in their household wells, and (c) experience in drying up of fountains and water resources at present compared with the past (1980–1990).

significant decreases in groundwater levels in both Diyathalawa and Haputale areas.

Based on the results, 85% of the people living in the Diyathalawa area, 80% of the people living in the Haputale area have experienced drying up of artesian wells and water resources, which they have used in the past (Fig. 7c).

Relation of water repellency to groundwater levels

Results clearly revealed that soils of both lands covered by eucalyptus and pine plantation forests are showing water repellent conditions. Water repellent condition as well as the water entry values are significantly high compared with eucalyptus soils (Figs. 3, 4, 5). Water entry values revealed that for the entry of water from the surface, eucalyptus soils would require a ponding depth of 4.6–5.3 cm, whereas the pine soils would require a ponding depth of 1.5–4.0 cm. Considering the topography, especially the slopes, of the study sites, it was clear that achieving these ponding depths would be difficult. For eucalyptus forest, attaining a ponding depth of above 4.5 cm would be almost impossible.

Modelling results revealed that the groundwater levels in the area of the eucalyptus forest diminished more dramatically, whereas the decline in the area of the pine forest was comparatively low. It was clear from the results that the groundwater recharge in the eucalyptus land was in a worse state compared with that in the pine forest land, suggesting endangered groundwater recharge in the highly hydrophobic eucalyptus land. Even with water repellent nature on the surface soils, presence of preferential flow paths in pine soils considered to be a possible process that supported groundwater recharging process.

CONCLUSIONS

The tested eucalyptus and pine forest soils showed very high water repellent levels on the surface. From the two soils, eucalyptus soils showed highly hydrophobic conditions. Considering the sloping landscape of the both areas, the surface runoff can be expected to become excessive. This would be the reason for the abundance of evidence of topsoil erosion in the area, which was more prominent in steeper slopes. Furthermore, achieving high ponding depths required for water entry would be difficult in these forested areas, more specifically in eucalyptus soils.

The modelling with remotely sensed thematic maps confirms that the groundwater levels in both areas, where the pine and eucalyptus plantations were located, has decreased exponentially over the time. Decline in the groundwater levels in the pine forest area was comparatively low, suggesting the presence of a successful process of groundwater recharge. Presence of preferential flow paths is considered to be a possible process for the groundwater recharge.

It was clear that the eucalyptus and pine vegetation have created unfavorable circumstances in regard with water entry and groundwater recharge. Proper attention from the responsible authorities will be essential to prevent the adverse impacts of on groundwater resource that can be considered as caused by introducing the exotic plant species, although the initial objective of introducing these plant species was to protect lands from degradation.

Conflicts of interest

As the authors of the manuscript, herewith we confirm that the study has not received any funds from interested parties, except for the UGC Block grant [RU/PG-R/16/01] and that there are no conflicts of interest in any manner.

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