In situ soil water repellency is affected by soil water potential rather than by water content as revealed by periodic field observations on a hill slope in a Japanese humid-temperate forest

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Abstract
To evaluate spatio-temporal occurrence of *in situ* soil water repellency in relation to soil moisture conditions, we periodically conducted field surveys in a humid-temperate forest in Japan. Measurements were made in 4 plots across a hill slope. Each plot contained 2 permanent quadrats (30 × 55 cm) with 48 measurement points per quadrat, where volumetric water content and water repellency of surface soil were measured. Most measurement points had critical water contents (CWC) below which soils repel water and above which soils were wettable. We assumed that the median CWC at 96 points per plot was the representative CWC (RCWC) for a plot, and estimated representative critical water potential (RCWP) from RCWC using water retention curves. RCWC differed, but RCWP was similar (pF = 3.5–4.0), between plots. Furthermore, water potential described the spatial fraction showing water repellency better than water content. These results suggest that water potentials, rather than moisture contents, are more indicative of the spatial occurrence of soil water repellency on hill slope areas. In the study site, surface soils on upper hill slopes tend to be drier and more frequently water repellent than lower parts, implying a greater tendency to generate surface runoff with rainfall events.

Key Words
Water repellent soil, water content, water potential, soil properties, spatial variability, temporal variability

Introduction
Soil water repellency, which has been observed worldwide, affects water movement such as surface runoff (DeBano, 2000; Doerr *et al*., 2000). Knowledge of water repellency distribution in soil surfaces would be useful in predicting the intensity of surface runoff on hill-slopes (Miyata *et al*., 2007). However, it is difficult to estimate water repellent areas by direct measurement when surface runoff occurs (Doerr and Moody, 2004), thus predictive indicators for water repellency need to be established.
Soil water potential might serve as a practical indicator for judging whether soil repels water without measuring water repellency *per se*. Disturbed soils that are potentially water repellent are reported to be so below water potentials of pF ≈3 and to be wettable above the water potentials (pF < ≈3) regardless of organic matter content or soil texture (de Jonge *et al*., 2007; Kawamoto *et al*., 2007; Kobayashi and Shimizu, 2007). We therefore postulated that soil water potential is indicative of water repellency across soils with varying physicochemical properties, even under field conditions. However, as most previous studies have used disturbed soil samples, there is inadequate information on the relationship between soil water potentials and water repellency under field conditions.
This study was undertaken to determine whether and how soil water potentials at soil depths of 0–5 cm indicated soil surface water repellency across a hill slope with varying soil properties; sites were within a humid-temperate forest in Japan. We also aimed to understand topographical conditions that influence water repellency within a hill slope.

Methods
Study site and soil properties
The study site was located in a humid-temperate forest administered by the Arboricultural Research Institute, University of Tokyo, Shizuoka, Japan (34°69′N, 138°8′E). Mean annual precipitation was 2,430 mm and mean annual temperature was 15.3°C in the period 2006–2007. We established 4 measurement plots located on different hill slope elements: P1 and P2 on a ridge, P3 on a shoulder, and P4 on mid-slope. The vegetation was secondary forest dominated by *Castanopsis sieboldii* (in all plots); *Alnus sieboldiana* and *Prunus jamasakura* also occurred in plots P2, P3, and P4.
We categorized soil structure by visual and hand inspection, and measured bulk densities using 100 cm^3 core

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samples to 5 cm depth. We took disturbed soil samples from the surface layer, (5 × 5 cm area, 1 cm depth) and ≈100 cm^3 samples from 0–5 cm depth. All samples were air-dried and dry-sieved through a 2 mm mesh. We determined soil textures, soil organic carbon (SOC) contents, C/N ratios, and soil pH (H_2O) of the 0–5 cm depth samples, and SOC contents and soil water repellency of the 0–1 cm depth samples. We performed particle size analysis by the wet sieving and pipette method (Gee and Or, 2002), and classified soil textures according to the system of the International Union of Soil Science. Total carbon and total nitrogen contents were measured with a NCS analyzer (NA 1500; Carlo Erba Instruments, Milan, Italy), and C/N ratios were calculated. The SOC was assumed to represent total carbon because soil samples were not calcareous. Soil pH (H_2O) was measured using a pH meter (D-24; Horiba Ltd., Kyoto, Japan) in 1:2.5 soil:water suspensions. Soil water repellency was measured by the molarity of ethanol droplets test (MED test) (King, 1981). We put subsamples >5 mm thick into plastic cups and dripped an ethanol solution (0–5 M range, applied at 0.2 M concentration intervals) through a pipette onto the flattened soil surface. We recorded the MED values as the lowest molarity of ethanol solution that was able to penetrate soil surfaces within 10 s. Water retention curves were made using the hanging water column method (pF = 0.0–2.1), the pressure plate method (pF = 2.1–3.7), and a psychrometer (pF > 3.7) (Dew Point Microvoltmeter HR-33T; Wescor Inc., Utah, USA) for soils sampled from 0–5 cm depth in mineral soils adjacent to quadrats in each plot (Dane and Hopmans, 2002a, b). The soil water potentials and soil water contents were fitted using the bimodal Kosugi soil water retention model (Seki, 2007).

Water repellency and water condition of surface soils

We established 2 permanent quadrats (each 30 × 55 cm) within each plot. At 48 points within each quadrat, we measured *in situ* water repellency and actual volumetric soil water content about twice a month during the period September 2006 to December 2007 (19–21 observations in total).We assumed that a soil was “water repellent” when water droplets remained on the surface for > 10 s (MED > 0 M), and was “wettable” when the retention time was < 10 s (MED = 0 M). We calculated the percentage of positions that were water repellent (proportion of 48 points) as a representative index of water repellency for each quadrate. Volumetric water content of the surface layer soil (0–5 cm depth) was measured using a soil moisture probe (ML2x Theta Probe; Delta-T Devices Ltd., Cambridge, UK) at points in quadrats adjacent to positions at which water repellency were measured. The sensor output was calibrated against water content for each plot. We determined the representative actual water contents of each quadrate (RAWC) as the median volumetric water contents of 48 points, and estimated the representative actual water potentials (RAWC) from RAWC and the soil water retention curve obtained for each plot.

Critical soil water conditions for soil water repellency

We determined the critical water content (CWC), above which the soil surface is wettable and below which it is water repellent, at every measurement point in each quadrate (48 points/quadrat). The CWC was calculated as the mean of the largest water content showing water repellency and the smallest water content when the soil was wettable. We determined the representative critical water content (RCWC) of each plot as the median CWC of 96 points (48 points × 2 quadrates) because there were similar frequency distributions of CWC in the 2 quadrats within each plot. We further estimated the representative critical water potential (RCWP, in terms of pF) from RCWC and the soil water retention curve obtained for each plot.

Results and discussion

Soil properties

Soil properties at 0–5 cm depth differed between plots; P4 had a less developed soil structure and a lower bulk density, P1 was less clayey and had a higher C/N ratio, and P2 had a lower SOC content than other plots (Table 1). All plots exhibited water repellency in air-dried 0–1 cm samples, except for one of 3 samples from P4 (MED = 0) (Table 1). The water retention curve of P1 differed from those of other plots, with lower soil water content at the same water potential when pF was >1.5. The relatively sandy texture in P1 may have caused this difference, as soil texture significantly affects water retention.

Table 1. Surface soil properties at each plot.

Plot ID	0–5 cm depth					0–1 cm depth	
	Soil structure	Bulk density ($g\ cm^{-3}$)	Soil texture	SOC content (%)	C/N	SOC content (%)	Soil water repellency (M)
P1	Moderately granular	0.65 (0.03, n = 3)	Sandy clay loam	7.6 (1.6, n = 6)	24 (3, n = 6)	14 (4, n = 8)	2.7 (0.3, n = 8)
P2	Moderately granular	0.67 (0.03, n = 3)	Heavy clay	4.6 (0.9, n = 5)	13 (1, n = 5)	15 (5, n = 6)	2.9 (1.2, n = 6)
P3	Moderately angular blocky	0.69 (0.04, n = 2)	Heavy clay	7.5 (1.6, n = 6)	14 (1, n = 6)	12 (2, n = 3)	2.3 (1.1, n = 3)
P4	Weakly crumb	0.59 (0.07, n = 3)	Light clay	7.5 (1.1, n = 5)	14 (1, n = 5)	11 (2, n = 3)	0.5 (0.6, n = 3)

Representative critical water content (RCWC) versus representative critical water potential (RCWP)
The RCWC was 0.16, 0.29, 0.28, and 0.27 m^3 m^{-3} for P1, P2, P3, and P4, respectively. RCWC in P1 was markedly lower than the other plots. On the other hand, RCWP values were similar between plots; pF = ≈3.7; 3.8, 3.9, 3.6, and 3.5 for P1, P2 P3, and P4, respectively. These results, which are consistent with previous work on disturbed soils, indicate strongly that RCWP is a more robust indicator of water repellency than RCWC at our study site where soil characteristics (soil structure, bulk density, soil texture, SOM contents, C/N ratio) and topographic conditions differed between plots (Table 1) (de Jonge *et al*., 2007; Kawamoto *et al*., 2007).
We found a poor relationship between RCWC and SOC contents ($p = 0.54$). This is inconsistent with previous studies on disturbed soils that showed a positive relationship between critical water contents and SOM contents (Regalado and Ritter, 2005; de Jonge *et al*., 2007; Kawamoto *et al*., 2007). Differences in RCWC may be largely attributable to different water-retention capacities, which in turn depend not only on soil organic matter contents but also on soil texture or other soil properties.

Critical soil water condition as an in situ indicator of 50%-area water repellency
The drier the soil, the larger was the water-repellent area (Figure 1). The relationship between RAWC and areal fraction of water repellency in P1 differed from other plots (Figure 1-a), whereas the relationships with representative actual soil water potentials for a quadrat (pF) (RAWP) were similar for all plots (Figure 1-b). Hence, RAWP explains the proportion of water-repellent area on soil surfaces better than RAWC at this study site, where soils varied in physicochemical properties and topographical conditions. The percentage area that was water repellent was well approximated against pF by a sigmoidal curve: $y = \alpha - \alpha / (1+e^{(x-\beta)/\gamma})$ where α, β, γ were 100, 3.7, and 0.25, respectively, and R^2 was 0.79.
We expect that half an area may be water repellent when RAWP is close to RCWP, although it is *not* mathematically proven. Observed data showed that about half the area of a quadrat was water repellent when RAWP was RCWP (pF = ≈ 3.7) (Figure 1-b). This also indicates that RCWP is actually "representative" in the sense that it may inform us whether or not more than half the area is water repellent.
The parameter α in the regression curve corresponds to the fraction of area (%) having the potential for water repellency. We set α as 100 because most measurement points showed actual water repellency and most 0–1 cm depth samples showed water repellency when air-dried (Table 1, Figure 2). If α is smaller than 100, the water-repellent area at RCWP is <50%. In that case, the spatial fraction of water repellent area may be determined not only by soil water potentials but also by the fraction of area having the potential for actual water repellency.

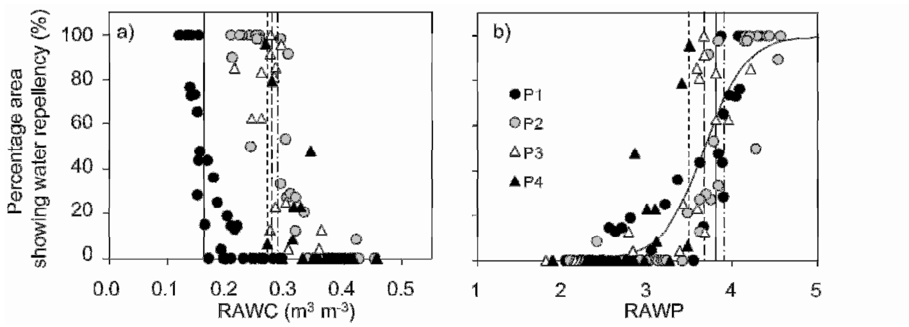

Figure 1. Percentage area showing water repellency as a function of soil water condition calculated from the number of water-repellent points divided by total observation points (48 points per quadrat). The x axis in (a) is representative water content for a quadrate (RAWC), which is identical to the median of 48 water contents in a quadrat; the x axis in (b) is representative water potential (pF) for a quadrat (RAWP) estimated from RAWC and water retention curves. Each point is a measure at each quadrat on each observation date. The same symbols are used for the 2 quadrates (a, b) in each plot. Solid line, dashed-dotted line, dashed line, and dotted line represent critical water conditions of P1, P2, P3, and P4, respectively. The sigmoidal curve was fitted against data for all plots, $y = 100\text{-}100/[1 + e^{(x - 3.7)/0.25}]$ ($R^2 = 0.79$).

Temporal distribution of water repellency as affected by topographic position
We estimated the common RCWP (50%-area water repellency) for all plots to be pF = 3.7 from the sigmoidal regression curve. Temporal fractions (against total observation dates) of RAWP drier than pF = 3.7 were highest at P1 and P2 (37% and 40%, respectively) which were located on ridges, were lower at P3 (15%) on the shoulder slope, and the lowest at P4 (0%) located on a mid-slope. These results were consistent with the temporal frequency in appearance of soil water repellency in each plot (Figure 2). Collectively, our

results show that surface soils on upper hill slopes tend to be drier and, as a result, water repellent more than twice as often as lower slopes. This implies a greater tendency to generate surface-runoff with rainfall events at these topographic locations.

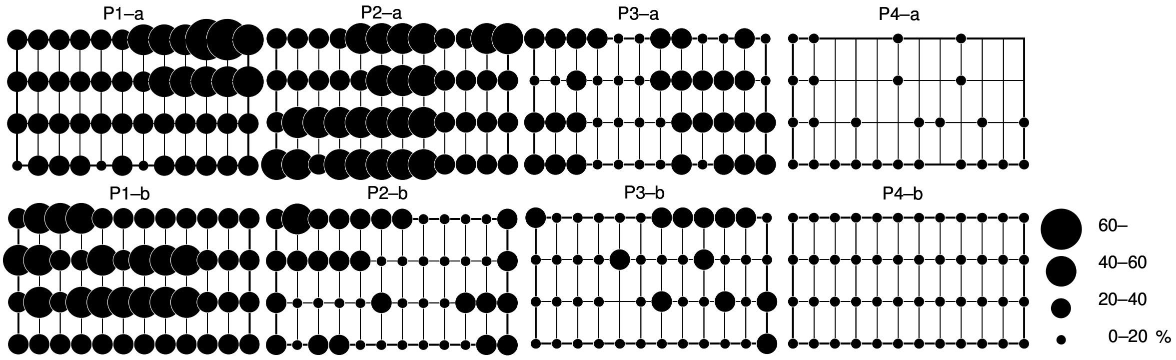

Figure 2. Proportion of occasions (percentage of 19–21 observations made between September 2006 and December 2007) when soils were water repellent at points within quadrats. Each lattice represents a quadrat within which measurements were made at 48 points. Each plot (P1–P4) consisted of 2 quadrats (a, b) . The size of each black circle represents the proportion of measurement occasions when soils were water repellent. The absence of a circle at lattice intersections indicates the soil was always wettable and was never water repellent at that position. P1 and P2 are located on a ridge, P3 on a shoulder slope, and P4 on a mid-slope.

Conclusion

Time-series field observations in a humid-temperate forest indicates that soil water potential, rather than soil water contents, at 0-5 cm soil depth is a practical indicator of the spatial occurrence of water repellency on soil surfaces in areas with varying physicochemical soil properties on hill slopes. We further suggest that the representative critical water potential (pF = ≈3.7) corresponds to a moisture condition with 50%-areal water repellency, given that the whole soil surface had a potential to repel water under certain water conditions, as observed in this study.

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The water content in the soil is a limiting factor for the production of grain in semiarid and arid regions, where potential evaporation is significantly larger than the amount of rainfall (Chi et al., 2009). The impact of precipitation (snowfall or rain) on productivity can be reinforced as a result of interaction with relief features and soil properties (Timlin et al., 1998; Kaspar et al., 2004).Â PAHs affect the activity of soil enzymes, which can be used to evaluate soil microbial properties (Shen et al., 2006).Â Erosion soil loss is much more sensitive to changes in slope steepness than the change of length, so the improved model USLE - RUSLE was aimed at the most accurate assessment of slope steepness factor (McCool et al., 1994). Direct and diffuse insolation. Fire can create, strengthen or destroy soil water repellency, with potential implications for soil infiltration, surface runoff and erosion. Laboratory studies suggest fire-induced changes to water repellency relate to soil temperatures during the burn. However, relations between temperature and repellency are rarely tested in the field where spatial variations in fuel type, soil type and soil moisture may lead to more complex responses to fire. Furthermore, few studies link point-scale water repellency measurements to hydro-geomorphic effects at larger spatial scales. A tolerable soil loss is the maximum annual amount of soil, which can be removed before the long-term natural soil productivity is adversely affected. The impact of erosion on a given soil type, and hence the tolerance level, varies, depending on the type and depth of soil. Generally, soils with deep, uniform, stone-free topsoil materials and/or not previously eroded have been assumed to have a higher tolerance limit than soils that are shallow or previously eroded. Soil loss tolerance rates are included in Table 6.Â Having obtained an estimate of the potential annual soil loss for a field, you may want to consider ways to reduce this loss to a tolerable level. Table 7 outlines management strategies to help you reduce soil erosion. Table 3A.