Assay of Soil Water Repellency of Coastal Forest Catchment in Subtropical Okinawa Island of Japan

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Abstract: This study was initiated to investigate the occurrence of soil water repellency (SWR), implications of SWR on hydrology, and possible causes of SWR in a selected catchment in Okinawa Island, Japan. Coastal forests in subtropical Okinawa archipelago are an important source of water supply. This function may be affected by SWR as SWR causes poor water infiltration leading to overland flows. To assess the SWR, sessile drop method (SDM) and in-situ and in vitro water drop penetration time (WDPT) tests were used. Being among the major factors influencing SWR, total soil organic carbon (TOC), water soluble organic carbon (WSOC), and soil texture were assessed. Nine transects, which included natural forest, secondary climax forest, and young secondary forest blocks consisting of abandoned plantation forests were studied. SDM results showed the existence of potential SWR in all the transects. The results of WDPT test and SDM were not directly comparable in the forest soil samples. In vitro WDPT test results showed the existence of potential SWR only in natural forest: Hikanzakura, and Iju plantation forests. However, none of the sites showed SWR during the in situ WDPT test. High soil moisture content may have masked the existence of SWR. A strong correlation was observed between WDPT and TOC ($r^2=0.89; p<0.05$). SWR occurrence and its severity appear to correspond well to the TOC when the latter is approximately 7-8% and above, in the soils of broad-leaved forests where trees are not specifically known for their role in causing SWR. These findings suggest that soil moisture and TOC have been the major determinants of the expression and occurrence of SWR respectively, for the catchment. However, if the regular moisture regime of the area continues to persist, the influence of water repellency on water infiltration and, hence on the hydrological processes will not be significant in the catchment.

Keywords: Soil water repellency; Coastal forest; Subtropical; Water drop penetration time test; Sessile drop method

1 Introduction

Since it was first described in early 20th century, the soil water repellency (SWR) has been reported from different areas of the world with varying environmental conditions at varying levels (Barrett and Slaymaker, 1989; DeBano, 1981; Roper, 2006; York and Canaway, 2000). Emergence of preferential flow paths, uneven and/or reduced water storage in the soil column, and Hortonian overland flow are some of the effects of SWR on hydrologic cycle (DeBano and Rice, 1973; Doerr and Moody, 2004; Doerr et al., 2000; Hallett, 2008; Kobayashi et al., 2002; Miyata et al., 2009a; Nagahama et al., 2001). In some regions of the world it has become so severe that amelioration methods have been attempted (Hallett, 2008; Roper, 2006). Studies have also shown the significance of considering SWR in runoff modeling though the real-time applications are much complicated (e.g. Doerr et al., 2003).

Research on water repellent soils in Japan dates decades back. Yamaya (1950) has reported that rainfall - soil moisture recharge relationship was not strong in Hiba (Thujaoccis dolabrata: Cupressaceae) forests. The phenomenon may be attributable to soil water repellency. Nakaya and Yokoi, (1973) and Nakaya et al. (1975, 1976) have done a series of presentations on their findings on fundamental aspects of soil water repellency such as influence of organic matter, and relationship between soil water and repellency etc. Along with the records as early as Nakaya et al. (1977), large number of research have focused on the characterization, measurement of SWR, factors affecting SWR, and effects of SWR (Kobayashi and Matsui, 2006; Kobayashi, 2007; Kobayashi et al., 1996; Leelamanie and Karube, 2007, 2009a, 2009b, 2011, 2012, 2013; Leelamanie et al., 2008b, 2010, 2008a).

Most of the applied research related to SWR have been done in temperate or warm-temperate regions of the main island of Japan. Among those, various research focused on the effects of SWR on hydrological processes under different tree plantations and natural forests. The soils under Japanese Cypress (Chamaecyparis obtusa: Cupressaceae) has got more attention as they have shown very high SWR levels especially under dry soil conditions. These studies, conducted under different conditions such as moisture regimes, forest structure, and topography have primarily attempted to clarify the hydrological processes such as surface runoff and bypass flow where soil water repellency is a potential causative factor (Ide et al., 2011; Kobayashi, 1999, 2008; Kobayashi et al., 2000; Miyata et al., 2009a). Potential SWR has been reported in other forests such as deciduous or broad-leaved forests but to a lesser degree (Gomi et al., 2008; Kajiura et al., 2010; Kobayashi and Matsui, 2006; Kobayashi et al., 2006).

Kawamoto and Banyar (2004) and Kawamoto and Hisato (2003) have investigated the water repellency in soils of volcanic origin. Their findings indicate the dependence of SWR on soil moisture content, organic matter, and...
soil structure. Repellency induced by fire has also been studied by various researchers (Kosugi, 2005; Obuchi et al., 2009).

In addition, the effects of SWR on overland flow generation and soil moisture content have been specifically investigated (Gomi et al., 2008; Kajiura et al., 2010; Miyata et al., 2009a, 2009b). In their findings, the influence of SWR on the hydrological processes has been recognized though the degree of influence has been found to depend on various other factors.

SWR is a phenomenon that reduces the affinity of soil to water (Doerr et al., 2000) or in ability of soil to get wet spontaneously when water is added (Leelamanie et al., 2008a) due to the higher cohesive forces than the adhesive forces (Doerr et al., 2000). Though mineral particles have high surface free energy than water, due to the presence of hydrophobic materials, wettability declines (Doerr et al., 2000; Leelamanie and Karube, 2009a). Usually organic matter acts as hydrophobic material (Mataix-Solera et al., 2007). The properties of organic matter determine the degree of hydrophobicity. Content of hydrophilic substances, their chemical characteristics and physical arrangement are among these properties. Soil micro-flora was also found to be responsible for SWR due to their secretions (DeBano, 1981; Hallett, 2008; York and Canaway, 2000). As surface area of the soil particles is important in terms of surface energy, the soil texture is also a major determinant of SWR (Hallett, 2008). High soil moisture has been found to suppress the expression of SWR (Leelamanie and Karube, 2011; Miyata et al., 2009a). Soil pH also affects the occurrence of SWR by manipulating the surface charges of soil particles and organic functional groups (Bayer and Schaumann, 2007; Hurraß and Schaumann, 2006). Forest fire may increase the SWR by facilitating the coating process of soil particles with hydrophobic organic substances (DeBano, 2000; Letey, 2001). Because of the complexity of the interactions of the above factors, explaining the SWR or its effect on other processes might be difficult in certain situations (Doerr et al., 2003).

Several methods are being used to characterize SWR. Most methods measure repellency as a relative measure (DeBano, 1981). Water Drop Penetration Time (WDPT) test is often used to determine the presence and persistence of repellency in the water-soil contact area due to its simplicity, repeatability, and applicability in field conditions (Dekker et al., 2009). As the water repellency is dependent on the soil moisture content, in situ measurements done by WDPT test may not be consistent and comparable. Therefore, various methods have been developed and being used to standardize the soil moisture contents in the laboratory and assess the variability of water repellency in terms of potential water repellency (Ike et al., 2011; Leelamanie et al., 2008). Liquid-solid contact angle measurement methods such as molarity of ethanol droplet method, sessile drop method (SDM) (Bachmann et al., 2000a, 2000b; Leelamanie et al., 2008a), and capillary rise method (Nakaya et al., 1977) are used to determine the degree of repellency. Among these methods, SDM has been rarely used in the assessment of SWR in the soils samples from the field.

As a large number of SWR related research are found focusing on the areas of main island of Japan, we recognize a need for an assessment of SWR in Okinawa as it is contrastingly different in terms of climate, soil, and vegetation compared to the main island of Japan. Coastal forests of subtropical Okinawa islands of Japan are ecologically and hydrologically important due to the rich biodiversity and as major sources of water supply (Ito, 1997; Yamashita et al., 2002). Due to the short length of the rivers, quick freshets and rapidly draining groundwater table, relying on the rain water is a problem even though Okinawa receives relatively higher amount of rainfall compared to the main island of Japan. Better understanding of underlying hydrological processes is a must for the water resource management. Hydrological features such as quick freshets, indicate the possibility of SWR occurrence in these catchments.

Therefore, the main objective of the research is to investigate the occurrence of SWR in a typical forest catchment of northern part of Okinawa Island (which also includes long unattended manmade plantation forest patches), clarify the degree of repellency and potential implications of repellency on the hydrological processes, and identify the major causes of repellency. A secondary objective is to investigate how sessile drop method and WDPT test results are related when applied to forest soil.

2 Materials and Methods

2.1 Site description

The site is a 318 ha experimental forest catchment of the University of the Ryukyus located in northern part of Okinawa Island (Figure 1). The natural and secondary forests all together occupy 85% of the catchment while the rest is unmanaged manmade plantations (Hirata, 1994). This catchment possesses typical features of the forests in the northern Okinawa. Okinawa forests are mostly secondary forests and can be categorized into young and old secondary forests. Old secondary forests are reported to be more than 50 years old. Most of the secondary forests are not subjected to management practices. Old secondary forests in the conservation areas are considered as intact forests. Relatively low species diversity has been reported in the secondary forests and the stratification was also found to be lacking. Secondary forests are dominated with Castanopsis sieboldii. The forests which are above 100 m above sea level are often getting drenched with low-lying clouds. Therefore, forests are mostly moist and possess certain features of the cloud forests (Kubota et al., 2005). For this study, old secondary forests are considered as secondary climax forests.

Climatic parameters calculated from meteorological data from 1981 to 2010 shows that the research site receives an average rainfall of 2500 mm per year which is comparatively higher than the 2000 mm average of Okinawa. The lowest rainfall is received during the month of December with an average of 138 mm. Average annual temperature is 20.7°C with January being the coldest with 14.5°C while July being the warmest with 26.7°C (Oku weather station of Japan Meteorological agency located appr. 11 km north of the study site). The topography is characterized by a moun-
tainous backbone with undulating to rolling terrain (slope range 25°-45°) where short and narrow streams extending towards the central backbone (Simonson, 1994). Slope characteristics and terrain features are presented by using digital elevation model (10 m resolution) developed by the Geospatial Information Authority of Japan.

Thirty six soil samples were collected from nine 15-20 m transects, each with four sampling points. Primarily, the sampling transects were selected to include the dominant stages of the forest succession: natural forest, secondary climax forests (>50 years old) and young secondary forests (<50 years old). In addition, the availability of information about the history of the forest, minimal interferences to the forest development, topography, and accessibility were also taken into consideration.

Natural forest had two transects, NAT 1 and NAT 2 located on a ridge and a slope lying surrounded by relatively high-lying areas respectively. The transect in the secondary climax forest was identified as SCF. The transect identified as APF is a young secondary forest left unattended for about 30 years. The original plantation was a Ryukyu Pine (*Pinus luchuensis* Mayr: Pinaceae) plantation. Other young secondary forests identified by the Japanese name of initially planted trees were selected as all these plantations forests are of similar age. They have not been subjected to any management operation, and they occupy a substantial area of a small sub-catchment (Figure 1) where parameters such as water discharge, soil moisture are continuously being monitored for other studies. Transects SUG, ISU, HIK, IJU, and EGO were selected in Sugi (*Cryptomeria japonica*: Taxodiaceae), *Distylium racemosum* (Hamamelidaceae), Hikanzakura (*Prunus cerasoides*: Rosaceae), *Ijju* (*Schima wallichii*: Theaceae) and Egonoki (*Styrax japonica*: Styracaceae) respectively. Total area of the plantations is approximately 5 ha and plantations were established in late 1970s and early 1980s and have been left unattended. Soil samples were taken from 0-5 cm depth (Šimkovic et al., 2009) after removing the litter layer as much as possible. Three 100 cc core samples were taken for subsequent soil evaluations. Sampling was done in December 2012 following about one week of dry spell. Initial moisture content, porosity, field capacity, bulk density and hydraulic conductivity were measured with soil cores. Soil samples were air-dried at room temperature and prepared for further analysis.

### 2.2 Test methods and analysis

**In situ** WDPT Test was done in each site by applying three 45-50 μl drops of deionized water. Relative humidity (RH) and the air temperature of the site were recorded (Dekker et al., 2009).

For the *in vitro* WDPT test, weighing bottles with 25 mm diameter and 30 mm height were filled with approximately 5 g of air-dried soil samples sieved with 2 mm sieve. Three replicates of each sample were kept in a chamber...
with 75% RH for a week for moisture stabilization. A drop of deionized water (50 ± 1 μl) was added from 10 mm above the soil surface in a room with RH 75 ± 5% and constant temperature of 25°C. During the time of water drop penetration, bottle was capped to stop evaporation (Leelamanie and Karube, 2012; Leelamanie et al., 2008a).

Samples for in vitro SDM were prepared by sieving air-dried soil with 1 mm sieve. A 15 x 15 mm double-sided tape was fixed to a glass slide in the middle of one side. Soil samples were sprinkled on to the double sided tape and fixed to the tape by pressing with another slide using a 100 g weight for 10 seconds. Excess soil was removed by gently tapping the slide. The procedure was repeated twice. Three replicates were prepared from each soil sample (Total 108). Samples were stored in a chamber with 75% RH for a week. 10 μl of de-ionized water was added to the soil layer with a micro-pipette in a room with 75 ± 5% RH and constant temperature of (25°C). A picture was taken within one second using a micro-camera. Contact angles were manually measured on micrographs. Average of left and right side contact angles were calculated (Leelamanie et al., 2008a).

Soil texture was evaluated with hydrometer method. Total soil organic carbon (TOC) was evaluated with dry combustion (SUMIGRAPH NC-220F). As a measure of hydrophilic material content in soil organic matter, water soluble organic carbon (WSOC) was extracted from 5 g of soil with deionized water (soil: water ratio of 1:10) by shaking the samples for 15 minutes at 200 rpm. The supernatant was filtered with No. 2 qualitative filter paper (Jones and Willett, 2006; Lu et al., 2011) and the carbon content was determined by TOC-L CPH.

Minitab™ 16 was used in the statistical analysis. One-way ANOVA along with Fisher test was used to compare means of WDPT, CA, TOC and WSOC to find significant differences across sites. Pearson correlation and regression fitting was used where necessary to assess correlations between repellency values (WDPT and CA) with TOC, WSOC and textural fractions.

3 Results and discussion

3.1 Soil and vegetation of the sampling sites

The dominant soil groups in the area are red soils and yellow soils (Yamamori, 1994), corresponding to Udults or Udepts in the USDA soil taxonomy (Kubotera, 2006). Parent material is reported to be Paleozoic phyllites or sandstone (Hirai et al., 1991; Simonson, 1994). Further, Nicol et al. (1957) described the geology of the northern Okinawa as highly deformed, metamorphosed limestone, sandstone, shale, and volcanic rock. Compared to the soils of the warm temperate parts of the main island of Japan, soils of Okinawa have higher degree of weathering. Kaolinite has been found to be the most abundant mineral. The soil is also characterized by comparatively low surface activity (Hirai et al., 1991). Soil profiles of the sampling sites were more or less similar in basic characteristics except NAT2 where blackish organic matter layer and conspicuous organic matter migration to lower horizons was observed. Almost all the sites had a 1-2 cm thick litter layer. The thickness of the brownish A horizon ranged from 2-5 cm where B horizon extended to about 50 cm depth. Signs of soil erosion or relocation of litter with runoff water is barely observable in the catchment despite the steep slopes. However, Sugi plantation had few exposed areas of the top soil close to the surface water flow paths. Further, contrasting differences of features such as exposure, vegetation, and litter layer were not visible within the sampling transects. Major soil characteristics are summarized in table 1. When the understory is dominated by Pleioblastus linearis: Graminaceae, a dense root-mat was observed surrounding the bushes. We observed that Pleioblastus linearis dominate the shrub layer in the areas where sunlight well reach the forest floor. Higher litter accumulation was observed when Alsophia spp: Cyatheaceae, are abundant in the shrub layer.

An assessment of vegetation of sampling transects is given in (Table 2). Natural forest had the highest plant diversity. Secondary climax forest had plant diversity comparable to natural forest but the sub-canopy was comparatively sparse. Intrusions of naturally occurring plant species were clearly visible in all the plantation forests except Sugi plantation. Isunoki plantation had dwarf forked trees and low plant diversity. The damage from a powerful typhoon struck three months before the sampling was clearly visible in the APF.

3.2 Level of SWR in the catchment and possible effects on the hydrological processes

During the field WDPT test, no repellency was observed at any sampling site. RH and temperature during the measurement were 83% and 17°C. However, results of the laboratory SDM and WDPT test conducted with air-dried soil provide evidence for the existence of potential SWR but not in extreme levels. Therefore, during the field test, highly moist soil environment may have masked the hydrophobic characteristics of the soil. The dependence of SWR on the

|           | NAT1 | NAT2 | SCF  | APF  | EGO  | HIK  | IU   | ISU  | SUG  |
|-----------|------|------|------|------|------|------|------|------|------|
| |
| \(D_b (g/cm^3)\) | 0.69 | 0.93 | 0.78 | 0.80 | 0.71 | 0.98 | 0.64 | 0.74 | 0.99 |
| Initial moisture (%) | 69.9 | 44.1 | 57.1 | 51.7 | 78.5 | 49.4 | 77.4 | 57.2 | 42.7 |
| SHC (cm/s) | 0.006 | 0.008 | 0.009 | 0.043 | 0.002 | 0.008 | 0.033 | 0.018 | 0.012 |
| Field capacity (%) | 60 | 59 | 56 | 56 | 61 | 55 | 58 | 57 | 50 |
| Porosity (%) | 62 | 61 | 57 | 57 | 64 | 56 | 59 | 57 | 51 |
| Soil Texture | CL | C/CL | CL | L | CL | C/CL | C/CL | C/CL | C/CL |
| Soil pH | 4.49 | 4.46 | 4.34 | 4.35 | 4.18 | 4.33 | 4.37 | 4.09 | 4.8 |
| TOC (%) | 8.57 | 14.12 | 6.37 | 5.18 | 5.4 | 4.98 | 5.49 | 4.97 | 5.31 |
| WSOC (%) | 0.09 | N.A. | 0.071 | 0.062 | 0.063 | 0.054 | 0.065 | 0.067 | 0.067 |

\(D_b\) - Bulk Density, SHC - Saturated Hydraulic Conductivity, C - Clay, CL - Clay loam, SCL - Sandy clay loam, L - Loam, N.A. - Data not available
antecedent soil moisture has been highlighted by many researchers. Runoff study in Japanese cypress plantations in central Japan has shown that the overland flow was high during the precipitation following a dry spell. They have also observed seasonal changes in the infiltration characteristics in the experimental soil and suggest that SWR induced by low soil moisture content could have partially involved in changing infiltration process (Gomi et al., 2009a). Miyata et al. (2010) reported SWR as a reason for uneven infiltration pattern of stemflow under Japanese cypress trees. Studies conducted under deciduous forests and broad-leaved forests in Japan have shown the existence of potential repellency but at a lower extents (Gomi et al., 2008; Kajiura et al., 2010; Kobayashi and Matsui, 2006; Kobayashi et al., 2006). Miyata et al. (2009a) suggests that the degree of influence of SWR on hydrological processes such as overland flow may depend on other factors. These findings are comparable with our findings for the subtropical evergreen coastal forests situated on a largely different geographical and geological setting.

Unlike in the main island of Japan, seasonal differences in climate are not strong in Okinawa in terms of total monthly rainfall. Northern Okinawa, in particular, receives relatively high rainfall distributed throughout the year maintaining relatively high soil moisture levels (Figure 2). Therefore, if the normal moisture regime of the area continues to persist, water repellency may not come into effect and hence, may not interfere in hydrological processes significantly. However, for the current catchment, the critical level of soil moisture where the repellency may come into effect and its persistence have to be further investigated. Forest fire could also induce repellency, particularly in natural forest where soil organic matter is relatively high. This phenomenon also needs further investigations as it may depend on the type of organic matter and the degree of burning (Obuchi et al., 2009).

### 3.3 Characterization of the level of SWR with WDPT test and SDM

The criteria to interpret SDM results are not well-defined. Theoretically, 90° contact angle indicates the existence of repellency (DeBano, 1981). However, water repellent soils have shown a wide range of contact angles (Bachmann et al., 2000b). Many authors have attempted to compare it with the categorization based on WDPT (Table 3). It has been shown that contact angles 70° to 88° may correspond with the categorization based on WDPT (Table 3).

#### Table 2: Characteristics of the vegetation in each transect

| Transect | Canopy Species (%) | Sub-canopy | Shrubs layer Spp (No. of Bushes) | Total stem count/ 25 m² (DBH > 5 cm) | DBH range (cm) | Height (m) |
|----------|--------------------|------------|---------------------------------|-------------------------------------|----------------|------------|
| NAT1     | Castanopsis sieboldii (50) Schima wallichii (20) Elaeocarpus japonicus Distylium racemosum | Syzygium buxifolium Camellia sasanqua Ternstroemia gymnanthera Ardisia quinquegona | Pleioblastus linearis - only in NAT 1 (15) | 10 | 3-39 | 5-10 |
| NAT2     | Castanopsis sieboldii (50) Schima wallichii Daphniphyllum glaucescens Elaeocarpus japonicas Ternstroemia gymnanthera Myrica rubra | Myrsine seguinii Dammacanthus biflorus | Pleioblastus linearis (17) | 11 | 4.5-30 | 3-10 |
| SCF      | Castanopsis sieboldii (50) Schima wallichii Daphniphyllum glaucescens Elaeocarpus japonicas Ternstroemia gymnanthera Myrica rubra | Myrsine seguinii Dammacanthus biflorus | Pleioblastus linearis (17) | 11 | 4.5-30 | 3-10 |
| APF      | Pinus luchuensis (30) Castanopsis sieboldii (20) Cinnamomum douderleinitii Persea thunbergii | Rhaphiolepis indica Syzygium buxifolium Ternstroemia japonica | Dicranopteris linearis (as a layer covering the ground) Pleioblastus linearis (4) | 9 | 2-15 | 4-9 |
| EGO      | Styrax japonica (<30) Schima wallichii (50) Distylium racemosum Castanopsis sieboldii (20) Elaeocarpus japonicus Machilus thunbergii | Sassafras albidum | Blechnum orientale L. (15) Pleioblastus linearis (6) | 17 | 4-12 | 6-8 |
| HIK      | Prunus campanulata (50) Schefflera octophylla | Scheflera octophylla Maesa montana Ficus bengutensis Wendlandia formosana | Blechnum orientale L. (15) | 24 | 4-15 | 9 |
| LIU      | Schima wallichii (60) Diospyros morrisiana Styrax japonica | Alsophila podophylla | Blechnum orientale L. (19) Pleioblastus linearis (1) | 23 | 3-12 | 3-5 |
| ISU      | Distylium racemosum (50) Castanopsis sieboldii (30) | Pleioblastus linearis (Numerous) Including stems < 5 cm | Blechnum orientale L. (15) | 21 | 2-10 | 3-5 |
| SUG      | Crypromeria japonica (100) | Pleioblastus linearis (Numerous) Including stems < 5 cm | Blechnum orientale L. (19) | 16 | 7-12 | 11-13 |
to slight repellency and all other higher categories of repellency may fall between 88° to 93° for model sand (Leelamanie et al., 2008a). For sandy soils of temperate pine forest, contact angles of 90° or above have corresponded to severely to extremely repellent, 80°-90° to slightly to strongly repellent, and less than 80° to non-repellent (Bachmann et al., 2000b).

According to the results of SDM interpreted based on the above criteria, especially the classification of Bachmann et al. (2000), all the sampling transects have some level of potential repellency. However, the results of the in vitro WDPT test define the level of repellency differently for some sampling transects (Table 4). APF and SCF have contact angles greater than NAT1 (slightly repellent under WDPT test) even though they do not display repellency under WDPT test. Similarly ISU with a contact angle greater than IJU do not show SWR. Despite having the lowest contact angle HIK soil shows slight repellency under WDPT test.

In view of understanding this discrepancy, individual repellency values of each sampling site from both methods were plotted against each other (Figure 3) and partitioned into different levels of repellency based on similar previous studies (Bachmann et al., 2000b; Leelamanie et al., 2008a). There was no observation of any particular pattern especially around the boundary of non-repellency to slightly repellency in both methods (80°/90° and 1 second in SDM and WDPT test respectively). The comparability of the results of the soil sample from the field may vary despite the good correlations observed under certain studies as cited earlier (Table 3). For example, in an assessment of SWR by Kawamoto and Banyar (2004), in volcanic soils using WDPT test, capillary rise method, and ninety degree surface tension method, the result of the latter has deviated from the other two tests. A possible reason for this difference could be that the influence of soil structure (mainly the aggregation) on water repellency may not have been portrayed in SDM results as the soil used in the SDM was used as a monolayer in contrast to the soil passed through the 2 mm sieve in WDPT test. A close association between SWR and soil structure in aggregated soils has been reported in a previous study by Kawamoto and Nakamura (2003). As

Table 3: Repellency severity categories based on WDPT (Leelamanie et al. 2008) and SDM (Bachmann et al., 2000b)

| Severity category | WDPT (s) | SDM (Degrees) |
|-------------------|----------|---------------|
| Non-repellent (NR) | ≤ 1      | < 80          |
| Slightly repellent (SLR) | 1 – 60 | 80 - 90       |
| Strongly repellent (STR) | 60 – 600 |     |
| Severely repellent (SVR) | 600 – 3600 | > 90       |
| Extremely repellent (ETR) | ≥ 3600 |       |

Table 4: Results of the SDM, in vitro and in situ WDPT test

| Transect | Mean contact angle (Deg) | Severity of repellency | Mean WDPT Test (In vitro) | Severity of repellency | WDPT Test (In situ) | Severity of repellency |
|----------|-------------------------|------------------------|---------------------------|------------------------|---------------------|------------------------|
| NAT2     | 100.25                  | SVR to ETR             | 175.24                    | STR                    | NR                  |                        |
| APF      | 96.75                   | SVR to ETR             | <1                        | NR                     | NR                  |                        |
| SCF      | 95.75                   | SVR to ETR             | <1                        | NR                     | NR                  |                        |
| NAT1     | 94.25                   | SVR to ETR             | 3.55                      | SLR                    | NR                  |                        |
| ISU      | 92.00                   | SVR to ETR             | <1                        | NR                     | NR                  |                        |
| IJU      | 90.75                   | SVR to ETR             | 1.04                      | SLR                    | NR                  |                        |
| SUG      | 86.75                   | SLR to STR             | <1                        | NR                     | NR                  |                        |
| EGO      | 83.25                   | SLR to STR             | <1                        | NR                     | NR                  |                        |
| HIK      | 80.50                   | SLR to STR             | 1.04                      | SLR                    | NR                  |                        |

Figure 2: Mean monthly rainfall (a) and mean monthly air temperature and relative humidity (b) around the study area (Japan meteorological agency Oka and Nago stations respectively – 1981-2010)

Figure 3: Relationship between contact angle (Deg) and WDPT (S)
both sets of samples were moisture-stabilized under 75% RH and 25°C the effect of moisture in expressing repellency could be assumed minimal. Therefore it can be suggested that the SDM has revealed the potential of soil to be repellent. On the other hand WDPT test has shown how the soil may exhibit repellency in its natural form where surface characteristics of the soil is altered by conditions such as aggregation and organic matter coating.

For detailed hydrological applications, we suggest measuring SWR combined with water sorptivity in an appropriate method (Vogelmann et al., 2010). This would provide pragmatic information about the influence of SWR on hydrological processes by taking various influential physical factors into account. Further, we would also like to suggest the use of air-dried and moisture stabilized undisturbed cores instead of sieved and processed soil for WDPT tests as it would take soil structural aspects such as aggregation into account.

3.4. Factors affecting SWR

The effect of soil moisture on the expression of repellency was described in the previous section. As major factors determining SWR, TOC content and the WSOC content of the samples were compared with the repellency values obtained from both methods. A strong correlation was observed between the TOC and the WDPT ($r^2=0.89$) irrespective of the site (Figure 4).

A similar pattern has been observed in a study investigating the effect of organic matter on water repellency with kaolinite and silica sand hydrophobized with Stearic acid. When increasing the Stearic acid content, a sharp increase in WDPT and contact angle has been observed from the boundary of slight repellency to extreme repellency (Leelamanie et al., 2010). Our results indicate that the repellency starts to increase rapidly and correlate well with TOC when TOC is approximately 7-8% or above. A similar pattern has been observed in another field study to assess the repellency under different tree species. Slight repellency has been observed in 3 out of 4 plant species where organic matter is above 7-8% (Mataix-Solera et al., 2007). In an investigation of the soil organic matter and initial moisture content of volcanic soil, it has been found that the extremely repellent soils have corresponded to carbon contents above 7.5% when volumetric water content was between 0.15 and 0.27 (Kawamoto and Banyar, 2004). The SWR assessed under the forests mainly with broad-leaved trees, by molarity of ethanol drop (MED) test has also shown that MED had been high for most of the observations when the total carbon content is above 7-8% (Kajiura et al., 2010). Therefore, we observe a trend in the relationship between total carbon and SWR under broad-leaved forests or trees. In these cases abundant organic matter may have encapsulated the soil particles lowering surface-free energy causing repellency. However, the origin and the type of organic matter and their physical arrangement which were not considered in this study could also be decisive factors in addition to the quantity. An example for this is the soil under Japanese cypress, well known for high SWR, has shown high MED values but very low correlation to the total carbon (Kobayashi and Matsu, 2006).

Contact angle measurements did not show a strong relationship to total organic matter content ($r^2=0.31$). A similar relationship ($r^2=0.22$) was also reported (Vogelmann et al., 2010). In their study the SWR measured as “repellency index” has also showed very low correlation to the organic matter ($r^2=0.185$) and it could possibly be due to the low organic matter content range (3-7.3%) in the soil.

The distribution of water soluble organic carbon across the sites is similar to the total organic carbon. Therefore, it does not significantly indicate differences in hydrophobicity of organic matter across the sites and, hence influence on repellency. Each soil textural fractions was compared with the WDPT and the contact angle and no significant relationship was observed. Organic matter encapsulation of soil particles and the aggregation could have masked the effect of texture on repellency.

3.5 Spatial variation of SWR

The natural forest has been found to have very high plant diversity (Ito, 1997; Kubota et al., 2005). Slight variations in the structure of the vegetation can be observed due to the degree of influence of typhoons and exposure to winds depending on the topographic variations (Kubota et al., 2005). In the sampling transect NAT1, forest floor is more exposed to wind and sunlight compared to NAT2 as its location is on a relatively open ridge (Figure 1). Abundance of Pleioblastus linearis in the shrub layer of NAT1 is a major difference between the two transects. Based on these observations we presume that the relatively low organic matter content in NAT1 can be attributed to the exposure of the forest floor and, hence faster decomposition rates. The difference of organic carbon content mentioned above could be a major reason for the larger differences in the potential water repellency observed in the transects located in the natural forest.

The secondary climax forest (SCF) also has comparatively high plant diversity but not as high as that of the natural forest. Most of the plant species found in the natural forest are found in the secondary climax forest. Although the transect is in a relatively enclosed area in terms of topography, the canopy cover is more or less similar to NAT1. Furthermore, the influence of typhoons and strong winds is not clearly visible in the site. The shrub layer is occupied...
mainly by *Pleioblastus spp*. On the other hand, the abandoned plantation forest (young secondary forest) has relatively low plant density and canopy cover. Most parts of the forest floor are covered by *Dichroantepis linearis* (Gleicheniaceae).

Although the sampling in the sub-catchment was done in different plantation forest blocks, intrusions of naturally occurring plant species were generally found in all the plantations. The shrub layer of the Isunoki plantation (ISU) is comprised mainly of *Pleioblastus spp*. Abundance of dwarf, forked and thin Isunoki trees is a prominent feature of the plantation allowing sunlight to reach the shrub layer. In addition, the plant diversity is also low in this plot. Egonoki (EGO) plantation on the other hand has relatively high species diversity and stand characteristics are more or less similar to the secondary forests. However, *Blechnum orientale* (Blechnaceae) is also abundant in the shrub layer. Sugi plantation also had *Blechnum orientale* as the shrub layer and almost no other plant species can be observed. Iju and Hikanzakura plantations also have relatively low plant diversity but intrusion of natural species can be clearly seen. *Blechnum orientale* is common in both plantations but *Pleioblastus orientale* is absent in Hikanzakura plantation while very sparse in Iju plantation. Therefore, it is difficult to isolate the effects of different plant species or communities on the emergence of repellency under these conditions.

4 Conclusions
Considering the results of both SDM and in vitro WDPT test, this study confirms that the surface of forest soil in northern Okinawa possesses potential water repellency at varying levels. Major factor that determines the severity of the potential repellency is the percentage of total carbon. High total carbon content in the soil promotes the occurrence of SWR. SWR occurrence and its severity appear to correspond well to the TOC when the latter is approximately 7-8% and above, in the soils of broad-leaved forests where trees are not specifically known for their role in causing SWR. High soil moisture reduces the occurrence of the repellency. In other words, SWR may not occur when the soil is sufficiently moist even if the soil is potentially repellent with high levels of total carbon. Therefore, if the regular moisture regime of the area continues to persist, the influence of repellency on water infiltration and, hence on the hydrological processes will not be significant in the catchment. The results of WDPT test and SDM were not directly comparable in the forest soil samples. A reason could be that the SDM does not sufficiently describe the effects of soil structural parameters (e.g. soil aggregation) on SWR. However, the results of the two methods may correlate well under high repellency levels.

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