OCCURRENCE OF SOIL WATER REPELLENCY IN THE NORTH AND SOUTH ISLAND UNDER PASTURE

P Jeyakumar[(1,*)], K Müller[(2)], J A Carter[(1)], C van den Dijssel[(1)], K Mason[(1)], R Blackburn[(1)], M Deurer[(1)] and B Clothier[(1)]

[(1)]The New Zealand Institute for Plant & Food Research Limited, Systems Modelling, Palmerston North;
[(2)]The New Zealand Institute for Plant & Food Research Limited, Systems Modelling, Hamilton
**Current address: Institute of Agriculture & Environment, Massey University, Palmerston North*

Introduction

Over many decades New Zealand's economy has mainly depended on dairy, sheep and beef farming, and therefore pasture production has been vital for New Zealand (Bryant & Sheath, 1987). Yet, soil moisture limits annual production of dry-land pasture (Thomas & Squires, 1991). Infiltration of water into soil is affected by various factors such as compaction, water repellency and surface sealing, which may enhance run-off (Doerr et al., 2000). Soil water repellency or hydrophobicity contributes to many environmental problems, including for example, flooding, accelerated soil erosion, nutrient leaching, pollution of water ways, and reduced groundwater recharge (Drewry, 2006; Müller & Deurer, 2011). It can also reduce pasture growth. Soil water repellency (SWR) is generally caused by organic compounds derived from living or decomposing plants or microorganisms (Doerr et al., 2000).

So far, only a few studies have surveyed the occurrence of SWR (Doerr & Ritsema, 2006). Recently, Mirbabaei et al. (2013) conducted a SWR survey considering ten forestry sites with different plant species in the Guilan province, North of Iran, and reported that SOM, texture and pH were the main soil factors for developing SWR. The persistence of SWR was positively correlated with the SOM (R=0.41) and negatively correlated with soil pH (R from -0.4 to -0.6). However, past studies did not investigate soils under pastoral land use in a wide range of geographical areas. For the first time in New Zealand, Deurer et al. (2011) conducted a survey on the occurrence of SWR in the top 4 cm of soils across 50 sites (ten major soil orders x five drought proneness classes) under dry-land pasture in the North Island. They highlighted the importance of SWR for New Zealand pastoral production systems and found that 98% of the sites became hydrophobic when they dried out, and that 70% of the sites were hydrophobic at field moisture level. In addition, they found a strong positive functional relationship between the degree and persistence of SWR. But SWR did not show any relationship with climatic variations, although the persistence of SWR was positively correlated with soil carbon and nitrogen, and negatively correlated with bulk density and soil moisture content. Based on the results of this survey (Deurer et al., 2011), we have extended and designed a survey to investigate the relevance of SWR in pastoral topsoils in the South Island of New Zealand. This paper combines the results of both surveys and analyzes how various soil and climatic factors influence the occurrence of SWR under pastoral land use in New Zealand.

Materials and Methods

Sampling locations

We conducted a survey on the occurrence of SWR in the top 4 cm of surface soils across New Zealand. Our hypothesis was that SWR is dependent on soil order and that it is correlated with the drought proneness of topsoils plus the summer rainfall in humid temperate regions. We selected 76 pastoral sites (Figure 1) by combining these three criteria. For the selection of pasture producing areas, we created a mask for 'grassland' land use in ArcGIS (ESRI, USA) by combining the land use categories 'high producing exotic grassland', 'low producing grassland', 'tall tussock grassland' and 'depleted grassland' of the Land Cover Database II (LCDB 2 – Ministry for the Environment, 2004; scale 1:50,000). We selected eleven dominant soil orders of New Zealand soil classification (Hewitt, 2010) under pastoral land use: Podzol, Organic, Recent, Pumice, Ultic, Gley, Brown, Pallic, Granular, Allophanic and Semi-arid.

We then stratified our sampling within the soil orders by a drought proneness factor, and annual summer rainfall. The drought proneness factor was a combination of soil dryness and amount of plant available water. As an indicator of soil dryness we chose the 'Annual Water Deficit' (AWD; Hewitt, 2010), which is the annual sum of any deficits between the monthly estimates of average daily rainfall and average daily potential evaporation (Priestley & Taylor, 1972). The amount of plant available water was indicated by 'profile readily available water' (PRAW; Hewitt, 2010), and was calculated from weighted averages over the profile section to a depth of 0.9 m, or to the potential rooting depth (whichever was the lower). We reclassified the AWD classes into three (0 = 0 mm, 1 = 1–50 mm and 2 = 51–396 mm) and PRAW was also reclassified into three classes (b = 0–49 mm, c = 50–74 mm and d = 75–100 mm). The detailed classification of drought proneness factor is explained in our previous publication (Deurer et al., 2011). The annual summer rainfall data were collected for the 30-year period from 1971 to 2000 (NIWA, 2011). The spatial data layer was again reclassified into three vectorised summer rainfall classes as follows: $L \leq 150$ mm (low), M = 150–350 mm (medium) and $H \geq 350$ mm (high). We then intersected these five data layers of land use, soil order, AWD, PRAW and summer rainfall to select polygons with different factor combinations.

To ensure accessibility of the sampling sites, we selected only polygons that are intersected by State highways or rural roads (NZTA, 2011). To ensure availability of sites under pasture, we selected only large polygons intersected by high producing pasture as specified in Land Cover Database II (MfE, 2004). The final sampling site, with a given factor combination was randomly selected from at least five properties and title holders, considering the closeness to roads and that the sites have not been irrigated. We transferred centroids for each selected property and polygons for each target polygon to an outdoor Global Positioning System (GPS) device (Garmin Dakota 20) and the same centroids to an automotive GPS device (Garmin nuvi 1390).

Field sampling procedure for the survey

The field sampling for the SWR survey was conducted in December–January 2009/2010 for the North Island, and for the South Island, the samples were collected in January 2012. At each of the 76 sites, five bulk soil samples (approximately 2000 cm^3) were taken in a star-shaped pattern, with each sample approximately 10 m apart. In addition, five bulk density core samples (45 x 50 mm inner diameter corer) were taken next to where the larger bulk samples were taken (n = 380 samples). The coordinates of each sample were recorded using a GPS device. In addition, an approximately 300 mm long and 30 mm diameter core was taken to measure the depth of the topsoil. We also recorded the presence or absence of worms, the slope and aspect, as well as any extra comments from the farmer. The bulk soil samples were stored in a cool room (4ºC) until analysis.

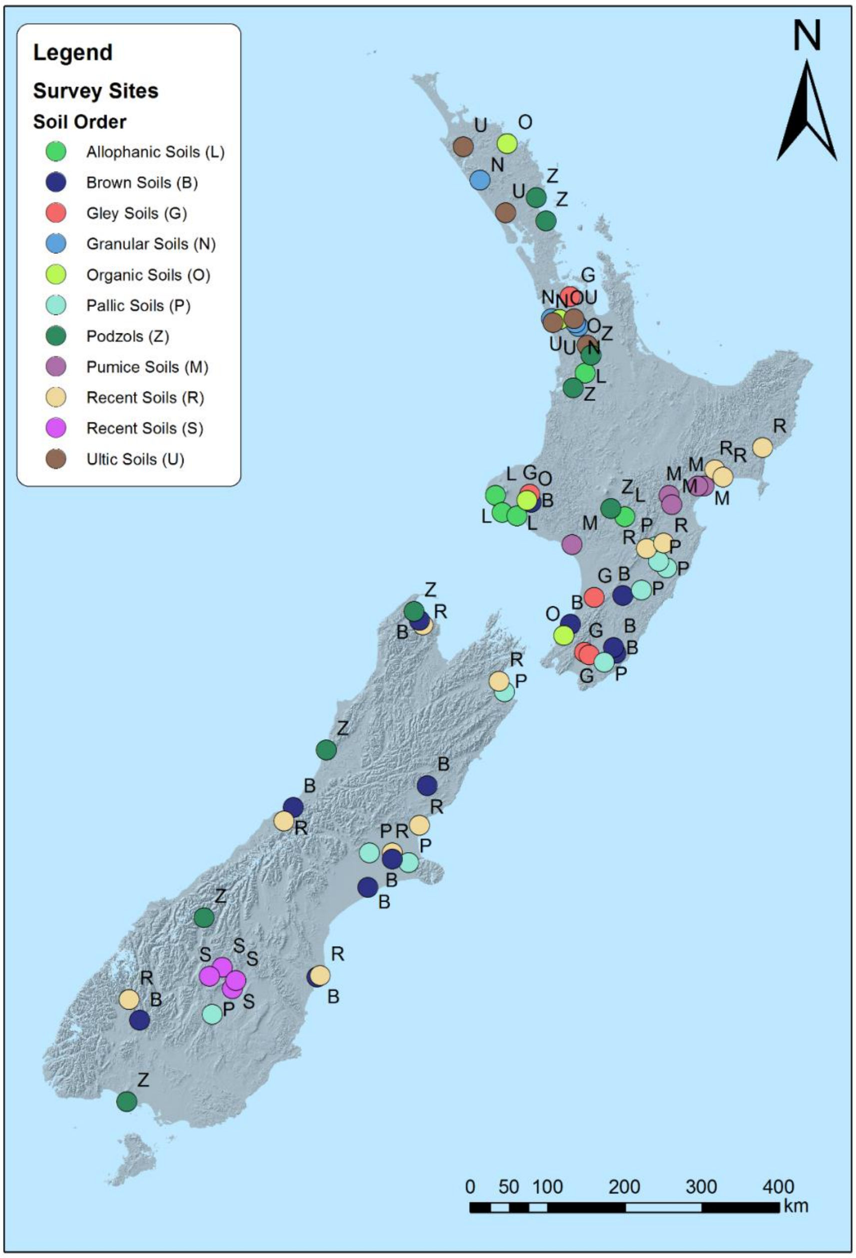

Figure 1: The final 76 sampling sites of the survey on the occurrence of soil water repellency in New Zealand considering eleven soil orders and three classes of each drought proneness and summer rainfall. State highways and rural roads were considered in the selection of sampling sites for easy accessibility.

Laboratory measurement methods for the samples of the survey

In the laboratory, the bulk soil samples were prepared for analysis. Initially, the thatch (~1 cm) was cut off and discarded. We collected 4 cm of the topmost layer of mineral soil, and the soil was then sieved through a 2-mm sieve. The degree of SWR was quantified by using the Molarity of Ethanol Droplet test (MED) (Roy & McGill, 2002). A subsample of ~60 g was used for the MED measurement to derive the degree of SWR. Soil was dried at 65ºC for

48 h (Kawamoto et al., 2007) prior to the MED measurement. A subsample of ~40 g was used for the water drop penetration time (WDPT) test. One half of this field-fresh subsample was directly used to derive the actual persistence of SWR using the WDPT test (Doerr et al., 1998) ($WDPT_{act}$). The other half was dried at 65ºC for 48 h before measuring the WDPT to derive the potential persistence of SWR (Doerr et al., 1998) ($WDPT_{pot}$). Detailed descriptions of the laboratory methodology are provided in Deurer et al. (2011).

In order to understand more fully other soil factors that are possibly related to SWR, additionally bulk density (Blakemore et al.,1987), pH, and SOM content were measured. A subsample of ~20 g was used for pH analysis using a Hanna HI 9812 pH meter according to Blakemore et al. (1987). A subsample of ~20 g was used for soil organic carbon (SOC) and soil organic nitrogen (SON) analysis. The Dumas method for %C was used to measure SOC using a Leco Truspec instrument (Blakemore et al., 1987), and for nitrogen we used an automated analysis technique (Tecator, 1983).

Statistical data analysis for unbalanced dataset

For each region and selected dominant soil order, replications of all possible factor combinations under pastoral land use were not equal and resulted in an unbalanced dataset. Therefore, we conducted an unbalanced analysis of variance, based on the effect of soil order in relation to summer rainfall or drought proneness classes on the appearance of SWR. For example, for the two factors of soil order and summer rainfall, both the effect of soil order adjusted for summer rainfall; and also summer rainfall adjusted for soil order on the degree and persistence of SWR were analysed. Site to site variation was included in the model, and soil order and summer rainfall effects were tested against this variation, because it was found that the differences between sites within the soil order–summer rainfall combinations were larger than the sample to sample variations within sampling locations. Similarly, we conducted an unbalanced analysis for variance for soil order and drought proneness classes. We interpreted the differences between averages of soil properties to be significant if they were larger than their respective least significant differences (LSD) at the 95% confidence level ($P \leq 0.05$). The analyses were performed using GenStat 14.2.0.6297 software (Payne et al., 2009).

Results and discussion

The measurement of the WDPT test indicated that 47 out of 76 sites (62%) of the field fresh top-soil samples (volumetric soil moisture varies from 7 to 75%) were hydrophobic at the time of sampling. The actual persistence of SWR is directly influenced by the soil water content at the time of sampling. The topsoils of 67 of the 76 pastoral sites (=88%) showed the potential to become hydrophobic if they were dried at 65ºC. Nine of the sites of the survey had a contact angle below 90°, the threshold for hydrophobicity, and thus were not hydrophobic. We could not determine a contact angle for these sites with the MED test, which is limited to measuring contact angles larger than 90° (Roy & McGill, 2002). These nine sites were excluded from the analysis presented in Table 1. According to the SWR ranking scheme introduced by Dekker & Jungerius (1990), the SWR of the air-dried samples was on average extremely persistent (Table 1). However, we found that the North Island soils were more prone to SWR than the South Island soils. Both potential persistence ($P=0.012$) and degree ($P=0.007$) of SWR were significantly higher in the North Island than the South Island.

Table 1: Overview of survey results. The soil properties of 76 sites (eleven soil orders x three drought proneness classes x three summer rainfall classes) were sampled in the top 4 cm of the soil under pastoral land use across New Zealand. Nine of the 76 sites were not hydrophobic (contact angle <90°) and were excluded from the calculation of the statistics for the contact angle.

Soil property	Mean	Median	CV (%)	Min.-Max
Contact angle (°)	96.8	97	3.9	90.4–104.1
WDPTpot (s)	1493.9	284.4	171.8	0.2–11880
WDPTact (s)	835.3	14.8	253	0–9948
SWR class[1] of field fresh samples (-)	3	1	119	0–9
SWR class[1] of air-dried samples (-)	4	3	72	0–9
Soil moisture (Vol.%)	33.6	32.5	41.5	7.1–74.9
Carbon (%)	8.9	7.5	73.1	2.6–40.6
Nitrogen (%)	0.8	0.7	54.9	0.3–2.9
C/N ratio (-)	10.8	10.3	14.7	8.3–16.5
pH(KCl) (-)	5	4.9	9.8	4.0–6.1
Bulk density (g cm^{-3})	1	1	25.4	0.5–1.5

[1]The SWR classes are: 0 – wettable; 1 – slightly persistent (5–60 seconds); 2 – moderately persistent (60–600 seconds); 3 – severely persistent (600–3600 seconds); 4 – extremely persistent (>1 hour). Class 4 is further subdivided into 5 – 3–6 hours; 6 – > 6 hours (Dekker & Jungerius, 1990)

The variability of the persistence of SWR was very high as indicated by the coefficients of variation (CV) of 253 and 172% for the actual and potential persistence of SWR, respectively (Table 1). The variability was lowest for the contact angle and soil pH. Other parameters such as bulk density, soil moisture, C/N ratio data showed moderate variability.

Impact of soil order, drought proneness and summer rainfall on the degree of SWR

The drought proneness did not show any significant effect on the degree of SWR (P=0.052). However, summer rainfall appeared to influence the presence of hydrophobicity (P=0.004), especially at high rainfall rates (>350 mm). Soil order did not have a significant influence on the degree of SWR (P=0.06). In general the degree of SWR was greatest for the soil orders Podzol and Organic, followed by Recent, and was least for the soil orders Allophanic and Pallic (Figure 2). The SOC content of this soil was the highest (14.6±9.4%) and had the lowest bulk density (0.8±0.2 g cm^{-3}) of the soils tested. Therefore, the accumulation of hydrophobic organic matter coatings on the surface of soil minerals may have increased the degree of SWR.

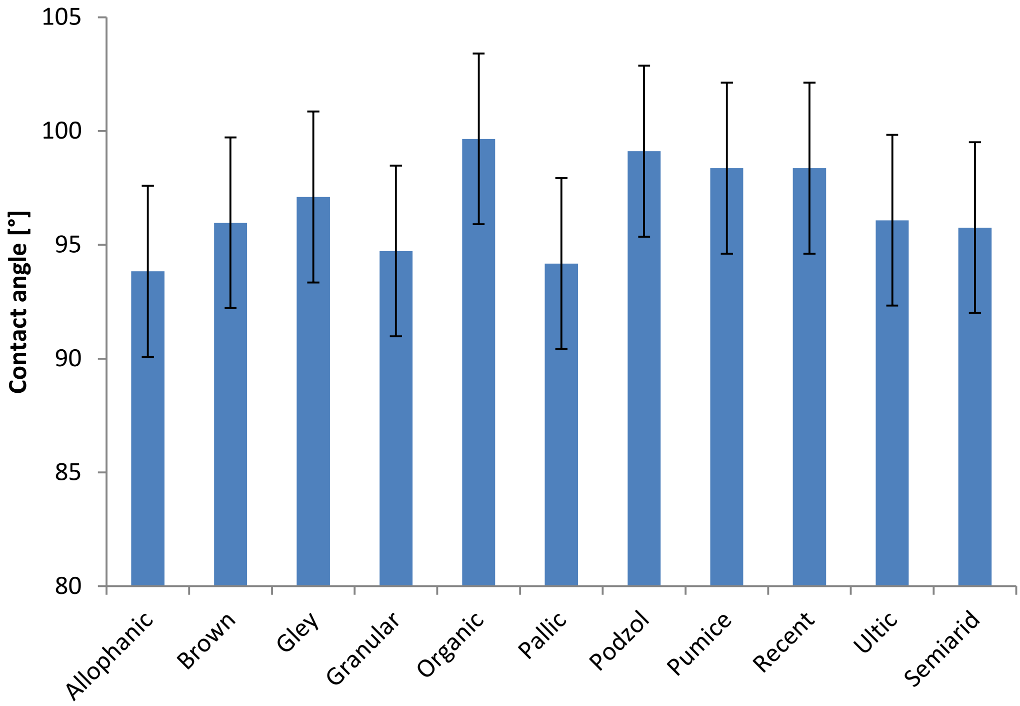

Figure 2: The degree of SWR of samples measured as contact angle with the molarity of ethanol droplet test from the top 4 cm of the soils covering eleven soil orders. The sites which had a contact angle of <90° (not potentially hydrophobic) were excluded from the analysis. The bars denote one standard error.

Impact of soil order, drought proneness and summer rainfall on the persistence of SWR

The data of the potential persistence of SWR were strongly skewed and the variability increased with the mean. Therefore, the data were log-transformed before conducting the unbalanced analysis of variance. We found that the persistence of SWR was also greatest for the soil orders of Podzol and Organic, followed by Recent and Pumice, and was least for the soil orders of Allophanic and Pallic, as observed for the degree of SWR. However, the variability of the persistence of SWR within the soil orders was extremely high (CV=172%), and the differences between soil orders were not significant (P=0.079). The drought proneness or summer rainfall classes did not show any significant influence on the persistence of SWR.

Relationship between degree and persistence of SWR

We found a significant positive relationship between the degree and the potential persistence of SWR (R=0.88, P<0.0001) (Figure 3). Thus, we could use the degree of SWR for analyzing potential correlations with other soil properties such as soil organic carbon, pH and soil particle distribution, instead of using the potential persistence of SWR, which has a high spatial variability and uncertainty in the measurements, especially if the persistence is high. Following Deurer et al. (2011), we also examined the 'critical contact angle', that is the contact angle above which the SWR can be expected to be at least moderately persistent (WDPT > 60 s). We found a critical contact angle of 93.6° for the entire survey (Figure 3). Deurer et al. (2011) found the critical contact angle was 93.8° for the North Island survey. These results also further demonstrate the reliability of the measurement of the contact angle for indirectly deriving the persistence of SWR. In addition, the measurement procedure of the contact angle (MED test) is faster than the measurement of the persistence of SWR (WDPT test). Thus, the critical contact angle might serve as a relatively quick and cost-effective measure for the likelihood that SWR leads to economic and environmental impacts under pastoral land-use (Deurer et al., 2011).

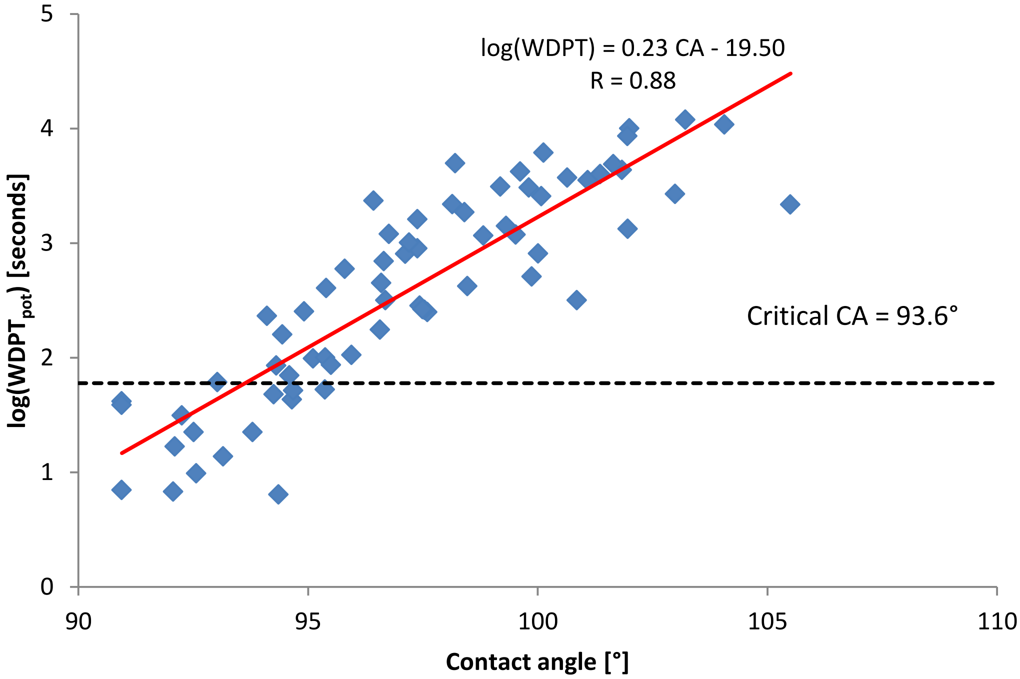

Figure 3: The persistence of SWR (log $WDPT_{pot}$) as a function of the degree of SWR (contact angle, CA) of 67 of the total 76 sites of the survey. Soil samples were taken with five replicates per site from the top 4 cm of the soils. Nine sites of the survey with a contact angle <90° (not potentially hydrophobic) were excluded from the analysis. The dashed line shows the log $WDPT_{pot}$ threshold of being moderately persistent (= $WDPT_{pot}$ of 60 s). The critical contact angle (see text for an explanation) is 93.6° (intersect between the dashed line and the regression line).

Relationship between soil properties and SWR and predicting the degree of SWR

A set of simple correlation analyses between various general soil properties including pH, bulk density and SOC content, and the degree of SWR (contact angle) and the persistence of SWR (log($WDPT_{pot}$) and log($WDPT_{act}$)) was performed using GenStat 14.2.0.6297 statistical software package. The nine sites of the survey with soils of a contact angle <90° (not potentially hydrophobic) were excluded from the correlation analysis between the contact angle and various general soil properties. All other correlations were performed with the entire dataset. The resulting correlation matrix with correlation coefficient values (R) is shown in Table 2.

The correlation analysis indicated that the degree of SWR was positively correlated with the soil SOC (R=0.49) and SON (R=0.47) contents, and negatively (R=-0.5) with bulk density. The pH values ranged from 4.0 to 6.1 and did not significantly (R=0.05) correlate with the contact angle. The persistence of SWR for field-fresh samples was negatively correlated with the soil water content (R=-0.55) (Table 2).

Table 2: Matrix with the correlation coefficients (R) of measured soil properties. The values describe the correlation of selected soil properties from the top 4 cm of the soils in New Zealand. The soil samples which had a contact angle of <90° (not potentially hydrophobic) were excluded from the analysis.

	Log $WDPT_{act}$	Log $WDPT_{pot}$	Soil water content	Bulk density	Organic carbon	Nitrogen	pH
Contact angle	0.41*	0.88*	-0.15	-0.50*	0.49*	0.47*	-0.05
Log $WDPT_{act}$		0.42	-0.55*	-0.18	0.23	0.20	-0.15
Log $WDPT_{pot}$			-0.13	-0.39	0.34	0.33	-0.03
Soil water content				-0.11	-0.04	0.03	-0.09
Bulk density					-0.71	-0.75	0.14
Organic carbon						0.97	-0.10
Nitrogen							-0.11

* P<0.001

If we use 60 s as the threshold for SWR being moderately persistent, we find that moderately persistent SWR only occurred for volumetric water contents below 47% (Figure 4). Doerr & Ritsema (2006) reported a critical water content of 37% in a survey on the occurrence of SWR conducted in the United Kingdom.

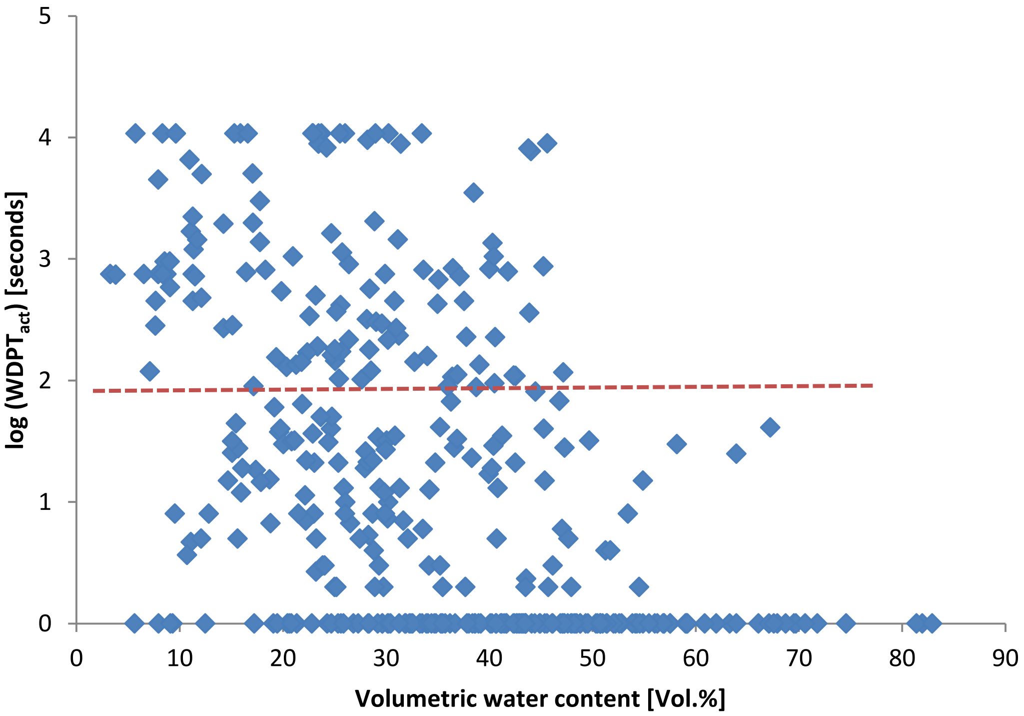

Figure 4: The actual persistence of SWR as a function of the volumetric water content. Samples above the dashed line have at least a moderately persistent SWR, and this occurs at critical volumetric water content below 47%. The samples were taken from the top 4 cm of 76 sites across eleven soil orders, three drought proneness and three summer rainfall classes. Within each site five samples were taken.

Conclusion

We conducted a survey on the occurrence of SWR in the top 4 cm of soils under pastoral land use at 76 sites across New Zealand. Our sampling sites represented the combination of eleven major soil orders, three drought proneness factors and three summer rainfall classes. The top-soils of 67 out of 76 pastoral sites (=88%) showed the potential to become hydrophobic if they dried out, and 62% of the field fresh top-soils were hydrophobic at the time of sampling in summer. Our survey confirms that SWR occurs in a wide range of soils. Our results contribute to the knowledge of which soil parameters affect SWR, and therefore may be useful in predicting its occurrence and severity in dry pastoral farm lands in New Zealand.

Acknowledgements

We greatly acknowledge the 'The Agricultural and Marketing Research and Development Trust (AGMARDT)' and the Sustainable Land Use Research Initiative (SLURI) programme for the financial support of this project.

References

Blakemore, L. C., Searle, P. L., & Daly, B. K. (1987). *Methods for chemical analysis of soils. New Zealand Soil Bureau Scientific Report 80. pp 103*.

Bryant, A. M., & Sheath, G. W. (1987). he importance of grazing management to animal production in New Zealand. Paper presented at the Proceedrngs 4th Animal Science Congress of the Asian-Australasian Association of Animal Production Societies, Hamilton, New Zealand.

Dekker, L. W., & Jungerius, P. D. (1990). Water repellency in the dunes with special reference to the Netherlands. *Catena Supplement 18*, 173-183.

Deurer, M., Müller, K., Van Den Dijssel, C., Mason, K., Carter, J., & Clothier, B. E. (2011). Is soil water repellency a function of soil order and proneness to drought? A survey of soils under pasture in the North Island of New Zealand. *European Journal of Soil Science, 62*(6), 765-779.

Doerr, S. H., & Ritsema, C. J. (2006). Water Movement in Hydrophobic Soils *Encyclopedia of Hydrological Sciences*. Malden, USA: John Wiley & Sons Ltd.

Doerr, S. H., Shakesby, R. A., & Walsh, R. P. D. (1998). Spatial variability of soil hydrophobicity in fire-prone eucalyptus and pine forests, portugal. *Soil Science, 163*(4), 313-324.

Doerr, S. H., Shakesby, R. A., & Walsh, R. P. D. (2000). Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews, 51*(1-4), 33-65.

Drewry, J. J. (2006). Natural recovery of soil physical properties from treading damage of pastoral soils in New Zealand and Australia: A review. *Agriculture, Ecosystems & Environment*, *114*(2–4), 159-169.

Hewitt, A. E. (2010). New Zealand Soil Classification (3rd ed.). Lincoln: Manaaki Whenua Press.

Kawamoto, K., Moldrup, P., Komatsu, T., de Jonge, L. W., & Oda, M. (2007). Water Repellency of Aggregate Size Fractions of a Volcanic Ash Soil. *Soil Science Society of America Journal*, *71*(6), 1658-1666.

Ministry for the Environment. (2004). Land Cover Database (LCDB) [WWW] document. Retrieved 07 July, 2011, from http://www.mfe.govt.nz/environmental-reporting/about/tools-guidelines/classifications/land/index.html

Mirbabaei, S. M., Shahrestani, M. S., Zolfaghari, A., & Abkenar, K. T. (2013). Relationship between soil water repellency and some of soil properties in northern Iran. *CATENA, 108*(0), 26-34.

Müller, K., & Deurer, M. (2011). Review of the remediation strategies for soil water repellency. *Agriculture, Ecosystems & Environment, 144*(1), 208-221.

NIWA. (2011). The National Institute of Water and Atmospheric Research, New Zealand (The National Climate Database). Retrieved 17 August, 2011, from http://cliflo.niwa.co.nz/

NZTA. (2011). New Zealand Transport Agency. Retrieved 11 September, 2011, from http://koordinates.com/layer/1331-nz-state-highway-centrelines-sept-2011/).

Payne, R. W., Murray, D. A., Harding, S. A., Baird, D. B., & Soutar, D. M. (2009). *GenStat for Windows* (14th ed.). Hemel Hempstead: VSN International.

Priestley, C. H. B., & Taylor, R. J. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review, 100*, 81-82.

Roy, J. L., & McGill, W. B. (2002). Assessing soil water repellency using the molarity of ethanol droplet (MED) test. *Soil Science, 167*, 83-97.

Tecator. (1983). Application note (AN62/83): Determination of the sum of nitrate and nitrite in water by flow injection analysis. Eden Prairie: Foss North America Technology.

Thomas, D. A., & Squires, V. R. (1991). Available soil moisture as a basis for land capability assessment in semi arid regions. In A. Henderson-Sellers & A. J. Pitman (Eds.), Vegetation and climate interactions in semi-arid regions (Vol. 12, pp. 183-189): Springer Netherlands.