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Workshop: Towards a better understanding of the causes, effects and remediation of soil hydrophobicity

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May 2010

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The report was prepared for Hawke's Bay Regional Council, Manawatu-Wanganui Regional Council, Gisborne District Council, Greater Wellington Regional Council, Taranaki Regional Council, and Environment Waikato and funded by an Envirolink medium advice grant (814-HBRC115) from the Foundation for Research Science & Technology

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Plant & Food Research, Palmerston North and Ruakura

SPTS No.	3949
PFR Client Report No.	38016
PFR Contract No.	24540

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Executive summary

Workshop: Towards a better understanding of the causes, effects, and remediation of soil hydrophobicity

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Project and Client

The workshop on soil hydrophobicity (SH) was undertaken on behalf of Hawke's Bay Regional Council (Ian Millner) and supported by Manawatu-Wanganui Regional Council (Grant Cooper), Gisborne District Council (Trevor Freeman), Greater Wellington Regional Council (Dave Cameron), Taranaki Regional Council (Don Shearman), and Environment Waikato (Reece Hill). It was funded by an Envirolink medium advice grant (814-HBRC115) from the Foundation for Research Science & Technology. The work was led by The New Zealand Institute for Plant & Food Research Limited (PFR) in collaboration with AgResearch Limited (AgR) as part of the Sustainable Land Use Research Initiative (SLURI).

This report details the contributions, discussions and practical demonstrations of the workshop "Towards a better understanding of the causes, effects, and remediation of soil hydrophobicity" that was held on 24th of February, 2010 at AgResearch Grasslands, Palmerston North.

Objectives

The workshop had three major objectives.

- To brief land managers from Regional Councils on soil hydrophobicity who will then pass the information on to farmers and use the information for developing a monitoring process for SH.

- To collate material drawn from a literature review for the workshop to develop resource material on the occurrence and management of SH, which the land managers can use directly with land owners.

- To develop skills in measuring soil degradation by SH, in interpreting and being able to explain the implications of SH on soil services and how a land manager might, through a change in soil and pasture managment, better manage soils.

Methodology

The workshop was organised in four sections

- Regional Council perspective
- Part 1 – Understanding soil hydrophobicity
- Part 2 – Measurement and monitoring of soil hydrophobicity
- Part 3 – Mitigation of soil hydrophobicity

The workshop consisted of six oral presentations, three practical hands-on demonstrations, and two group discussions.

Key results

These were the major results from the presentations and discussions:

- The measurements of SH are well developed, but other factors that influence SH such as vegetation type and management are often neglected. The causes of SH, as well as the environmental and economic impacts of SH, are still poorly understood, especially for New Zealand's soils and climatic conditions.

- SH is related to the patchy pasture growth termed the 'Dry Patch Syndrome'. It can lead to less pasture growth and, for example, for the Maraetotara Region in Hawke's Bay a yearly loss of about 35% or about 4 t of dry matter per ha equivalent to about $NZ400/ha was estimated. Direct measurements of the economic impact of SH at the field scale are needed.

- First results of a survey on the occurrence of SH across all soil orders and regions of the North Island found SH to be widespread and not closely related to soil order, climate or region. This agrees with research results from other countries.

- Various strategies for the mitigation of SH such as the application of lime exist, but so far, no field trials on soils other than coastal sands have been undertaken in New Zealand.

Recommendations

A group discussion of all participants at the end of the workshop resulted in the following top ten recommendations for future activities around SH:

1. What are the key factors causing SH in New Zealand – more research is needed
2. Test various mitigation treatments and devise protocols for mitigation treatments – Apply for a Sustainable Farming Fund project on mitigation with on-farm monitoring
    - Qualitative on-farm research
    - Accompanied by robust quantitative research
3. Quantify economic/environmental impact of SH
4. Quantify the water quality impact at the national scale; link to soil water quality via Regional Councils
5. Study SH in relation to water use efficiency and rainfall management
6. Identify and introduce soil quality indicator for SH
7. Fertiliser industry: Area of soil amendments (mitigation of SH) as a new growing industry
8. Prepare a fact-sheet on soil hydrophobicity
9. Circulate presentations to all participants
10. Submit a contribution to Grasslands conference and consider a contribution for the farming newspaper *Countrywide*

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1 Introduction

1.1 Context of the workshop

Soil hydrophobicity (SH) is an emerging problem for the pastoral industry, especially for locations without access to irrigation as it is triggered by droughts. SH is the seasonal inability of soil to enable infiltration of all the rainfall where it lands, and to store that water in the soil as a supply for plants and soil fauna. Therefore, SH seasonally threatens the soil's key ecosystem service of water regulation, and the provisioning ecosystem service, pasture production. Poor, patchy pasture growth is a feature of landscapes that suffer from SH. The increased risk of surface run-off in summer and autumn is real. This can aggravate the eutrophication of waterways and lakes.

The complexity and seasonality of SH still prevents its wider acknowledgement as a serious problem. In 2007, J. Morgan described SH in the Dominion Post "…because it is a transient phenomenon, its effects are masked – once it is all green again we forget it and move on, until next time. It becomes a double whammy, and the condition won't go away."

Through several small projects supported by AGMARDT, we could demonstrate a link between SH expressed as the Dry Patch Syndrome (DPS) and reduced pasture productivity in hill-country pastures. DPS is considered to be a widespread phenomenon in hill-country pastures, and can reduce pasture production by about 30%, reducing the profitability and future growth of sheep and beef production.

With this evidence showing that SH is a widespread phenomenon, it is very timely to reflect on (1) the current recommendations we and other agencies provide to land owners and (2) the current level of monitoring of our soil resources.

A workshop is the ideal platform to bring together current knowledge sets on

- when and how SH occurs,
- what the damage of SH is and if it is reversible,
- how best to monitor SH, and
- to determine the financial implications of doing nothing.

The workshop is also intended to progress how best to collate and present current knowledge to land owners and to identify any major gaps in present knowledge.

1.2 Environmental benefits of the workshop

SH reduces water infiltration and storage in the period from late spring to autumn. In affected areas, especially hill-country pastures, SH reduces pasture growth and increases surface run-off, and the potential for erosion events. For example, many studies have found that the main process for the transfer of P and various pesticides from agriculturally used areas into waterways in New Zealand is surface run-off. A better understanding of SH, its causes and remediation strategies will help land managers from Regional Councils to pass the information on to farmers and help them to develop strategies for monitoring SH. As a consequence, we expect for affected areas, a reduction in surface run-off and erosion, and by this an improvement of the water quality in nearby water resources and a reduction of soil loss.

2 Overview and structure of the workshop report

2.1 Goals of the workshop

The workshop was primarily for briefing land managers from Regional Councils who will then pass the information on to farmers and use the information provided for developing a monitoring process. Material for the workshop was drawn from a literature review to develop resource material which the land managers can use directly with land owners, with respect to the occurrence and management of SH. Developing skills in measuring the soil degradation by SH, interpreting and being able to explain the implication of SH on soil services and how a land manager might, through a change in soil and pasture managment, better manage the soil resource.

2.2 Regional Council perspective - *Ian Millner*

In the following paragraphs Ian Millner, a Land Management Officer from Hawke's Bay Regional Council, a farmer, and the initiator of the workshop, outlined the importance of the workshop and of SH for the Regional Councils.

Over the last four seasons Hawke's Bay pastoral agriculture has been severely affected by drought and prolonged dry conditions into the autumn. The cost of the droughts 2007 through 2009 reduced GDP on the East Coast of the North Island by about $1 billion. In Hawke's Bay, farm gate returns from the sheep and beef sector alone contribute 15% of regional GDP. The effects of hydrophobicity need to be researched further as it most certainly exacerbates the effect of drought and slows down any recovery.

Hawke's Bay, for all its droughts, is a region with good average rainfall in comparison to most of the agricultural regions in New Zealand, and better than in many parts of the world. Yet the region still seems to enter drought mode at the mere sniff of a dry spell. In fact, when individual rainfall events in the Bay are analysed over the last 23 years, greater than 50% of events over 20 mm have occurred during summer (October-March). The challenge for Hawke's Bay farmers is to develop production systems that can cope with intense but irregular rainfall. Climate change predictions suggest that this pattern is most likely to be exacerbated – that is, higher summer rainfall in intense but increasingly irregular bursts. Therefore, the ability to capture and use this rainfall will become vital for the long-term viability of the non-irrigated pastoral sector. Hydrophobicity is a soil condition that will need to be managed in order to meet these challenges.

The effect of prolonged drought on the typical family owned and operated unit from a social perspective is difficult to assess, but is probably the most damaging effect of drought. In the third week of March during the drought of 2008/09, I visited one of my clients who farms in the coastal hill country south of Waipukurau. He had been lucky enough to enjoy 150 mm of rainfall during February and thought his drought was over. However by mid-March, pasture growth had stopped and his pastures were regaining their pre-rainfall brown state. As I inspected this property I could clearly see how patchy the response to the previous month's rainfall had been. I knew the soils on this property (and most of his neighbours) were in a hydrophobic state. As I was observing this I was talking to the farmer and hearing all too familiar "stress talk". I was observing broken gear that previously would have been repaired to a good standard, either being patched or just left, carefully bred capital ewes with condition scores of 1 $^{1}/_{2}$ – 2 with the ram, and every water dam was 2/3 down and dropping. This guy was down mentally, he was financially stretched to breaking point (and still is) and he was physically exhausted – he was on his knees. I wanted to tell him what I thought was happening to his pasture and soils, but as I could not offer him a solution, I said nothing. This guy just did not need another problem to think about and least of all a problem he couldn't do anything about. From personal experience, I knew that feeling of helplessness - of being all out of options - is the worst feeling of all when droughts worsen. This was not an isolated case. Twelve months on, the rural support coordinator in Hawke's Bay is still working hard and picking up new cases of hardship and despair.

It is not often mentioned that events of real hardship in the rural industries are major drivers in turning the younger generation away from agriculture as a career. This situation threatens the reputation that agriculture has as a leading, innovative, adaptive industry. This is a threat to everyone involved with or dependant on agriculture in this country. We will never grow our industry while this situation continues. It is an issue of critical importance.

Concern about freshwater quality is widespread in New Zealand as pressure comes from agricultural intensification and urban pressure. Hawke's Bay is not immune to this problem. There has been the much publicised Taharua River situation and the Tukituki River is constantly under scrutiny.

It is clear that in order to keep our streams clean and healthy we need to keep the effects of agriculture on the land as much as possible. When issues like the Taharua and Tukituki make it into the media, no one wins. The situation invariably becomes political and resources get diverted to address the issues. Water quality problems need to be addressedwhere they occur – on the land, and not in the waterways. We need to be preventative not reactive. The role of hydrophobicity in increasing the occurrence of overland flow needs further quantification. Intense summer rainfall events can exceed a soil's capacity to absorb by 2-3 fold in an hour. This results in significant spikes of nutrients and coliforms entering water ways. Anything that can improve the soil's ability to absorb and retain summer rainfall will have real benefit for in-stream water quality and pastoral sustainability.

There is a desperate need for further objective research on the condition of hydrophobicity. As outlined, it has an effect at the economic, social, and environmental levels. In my opinion it is one of the most serious issues facing farmers on the East Coast. Climate change adaptation scenarios indicate that this issue needs to be addressed to enable adaptation to changing climatic patterns. It is very encouraging that some of our best minds are starting to focus on this issue and that there is a genuinely cooperative approach between the researchers. I think Regional Councils can play a significant role in support of this work.

I want to know if hydrophobicity is a problem in itself or a symptom of some other systemic failure. I want to know what the real drivers of hydrophobicity are and most of all I want to know what we can do about it.

2.3 Part 1 - Understanding soil hydrophobicity

The first three contributions of Part 1 set the scene and were followed by a group discussion.

Overview – What is soil water repellency/hydrophobicity, and why do we bother about it? (see Section 3.1). The overview explains SH, its measurement, presents the current state of knowledge on its causes, and describes its environmental and economical consequences. For this report, this section was extended by a literature review.

Hydrophobic compounds in coastal sands: extraction, characterisation, and proposed mechanisms for repellency expression (see Section 3.2). The presentation presents and discusses the hydrophobic compounds that cause SH using the example of coastal sands in New Zealand.

Soil hydrophobicity – Its significance to pastoral farming – The Hawke's Bay experience (see Section 3.3). The occurrence of SH in Hawke's Bay, the financial impact of SH-induced pasture loss and possible mitigations strategies of SH are presented and discussed.

A group discussion followed on observations of SH or something with similar symptoms in the different regions of the North Island (see Section 3.4).

2.4 Part 2 – Measurement and monitoring of soil hydrophobicity

Three practical demonstrations gave the workshop participants the opportunity to see and test for themselves

- ***how the persistence and degree of SH can be measured (see Section 3.5.1),***
- ***that SH reduces the infiltration rate of water into soils (see Section 3.5.2)***, and
- ***that SH generates run-off and overland flow (see Section 3.5.3)***

This was followed by the contribution ***'Soil water repellency survey of the North Island' (see Section 3.6)*** presenting results from an ongoing research project on the occurrence and consequences of SH.

2.5 Part 3 – Mitigation of soil hydrophobicity

The third part of the workshop focused the discussion on mitigation options for SH and finished with a group discussion on activities required in the short and long term to address the problem of SH.

The occurrence of soil hydrophobicity in golf course fairways and its management and control (see Section 3.7) presented and discussed SH as soil degradation on golf course turfs and suggested several mechanical and biological methods of mitigation.

The workshop closed with a group discussion around three topics.

- ***What activities are needed to improve the education and awareness with respect to SH (see Section 3.8.1)?***
- ***What activities are needed to close the research gaps with respect to SH (see Section 3.8.2)?***
- ***What are the top ten recommendations for future activities around SH (see Section 3.8.3)?***

3 Workshop - Contributions

3.1 Overview - What is soil water repellency/hydrophobicity and why do we bother about it – *M Deurer and K Müller*

This section contains the material presented at the workshop, and was extended by a literature review.

3.1.1 Introduction

Soil water repellency (SWR) is the phenomenon when a soil does not wet up spontaneously when water is applied to its surface (Figure 3.1.1). It is a transient soil property and will occur whenever soils dry out below a 'critical soil water content', which might occur more often given the extent to which climatic extremes and droughts have been forecast for most regions in the wake of climate change (Meehl *et al.* 2007; Watson 2001). The importance of SWR for different ecosystem services that soils provide has been acknowledged, including support of plant growth for food and fibre production (Bond 1972), water retention, infiltration and run-off leading to flooding and erosion (Doerr *et al.* 2000a; Wallis and Horne 1992), filtering of agrichemicals (Aslam *et al.* 2009b) and sustaining the stability of aggregates (Blanco-Canqui and Lal 2009; Wang *et al.* 2000). A true understanding of the ecological significance of SWR, however, is still very limited. The spatial extent of SWR in New Zealand and its importance for the economy is unknown.

Figure 3.1.1. The phenomenon of soil water repellency.

3.1.2 SWR and hydrophobicity

SWR results from the interaction of water with the soil's particle surfaces. This interfacial interaction is mainly controlled by the interfacial tension, defined as the surface energy per unit area of the interface between two phases. Each phase by itself is characterised by its surface tension, which actually is the interfacial tension between this phase and a gas (the identity of which is unimportant because of its very low density). In soils, water with a high surface tension of about 72 mN m^{-1} plays a dominant role. Surface tensions of soil particle surfaces may range from 20 to 60 mN m^{-1}. Hydrophobicity/hydrophilicity of a surface can be quantitatively measured by the equilibrium contact angle (CA) that water makes with this surface in air. The CA is defined as the angle (°) formed between the tangent to the solid-air interface and the tangent to the liquid-air interface at the three-phase contact line, measured on the water side (Figure 3.1.2). The CA on ideal solid surfaces (i.e. smooth, rigid, chemically homogeneous, insoluble and non-reactive) is related to the interfacial tensions:

$$\sigma_{LV} \cos(CA) = \sigma_{SV} - \sigma_{SL} \qquad (1)$$

where σ_{SV} is the surface tension of the solid-gas interface, σ_{LV} is the surface tension of the liquid-gas interface, and σ_{SL} is the solid-liquid interfacial tension. This CA is referred to as the ideal CA. Although CA values may vary continuously depending on the surface tension of the solid in question, it is convenient to think in terms of three different wetting situations (Figure 2): Complete wetting, for which the ideal CA is zero and the liquid forms a very thin film, partial wetting with 0° < $CA \leq$ 90°, and partial wetting with CA >0°, which is sometimes referred to as non-wetting. A soil with a CA larger than 0 degrees is water repellent, and a soil with a CA equal or larger than 90 degrees is hydrophobic.

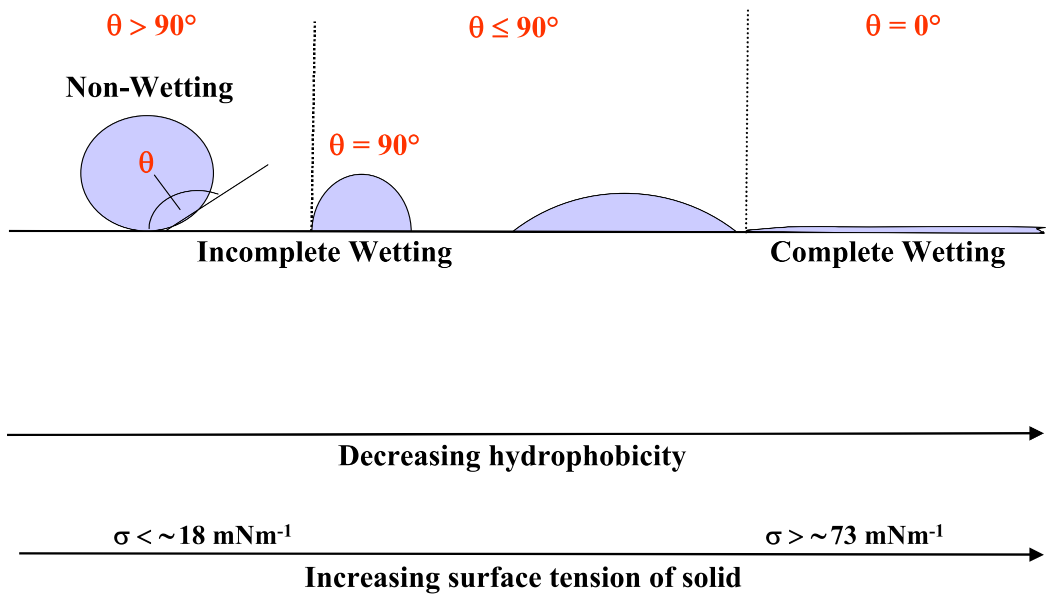


Figure 3.1.2. Schematic representation of the various degrees of hydrophobicity and the corresponding solid surface tensions. The contact angles CA are represented by the symbol θ in the figure. The figure was taken from the Encyclopaedia of Soil Science (Bachmann *et al.* 2005).

SWR is not a static soil property, because the water content can alter the wetting properties. Conceptually, three key site-, soil- and climate-specific properties need to be known to predict the phenomenon of hydrophobicity in soils:

1. ***The degree of SWR*** in form of the contact angle of the air-dry soil. This maximum contact angle describes the maximum SWR for the site that might be reached after prolonged dry periods.

2. ***The persistence of SWR*** in form of the time that is needed for water to infiltrate through a water repellent surface. During rewetting the maximum contact angle of a water repellent air-dry soil gradually decreases until water can infiltrate.

3. ***The critical water content*** below which SWR occurs**.** The maximum contact angle only occurs below a site-, soil-, and climate-specific threshold, the critical water content.

3.1.3 Measuring SWR

The ***degree of SWR*** can be approximated with CA between a drop of an aqueous ethanol solution and the soil surface (Roy and McGill 2002). For hydrophobic soils, the CA between water and the soil surface is larger than 90 degrees (Figure 3.1.3a). The molarity of ethanol-droplet (MED) test can be used to quantify the degree of SWR in hydrophobic soils (CA > 90°). In the MED test the surface tension of the wetting liquid, an aqueous ethanol solution, is varied to the point where the soil spontaneously adsorbs the liquid, and the contact angle between the soil surface and the liquid is 90°. Usually, the soil is oven dried at 65°C for 48 h and then equilibrated for 24 h at room temperature before conducting the MED test (Kawamoto *et al.* 2007).

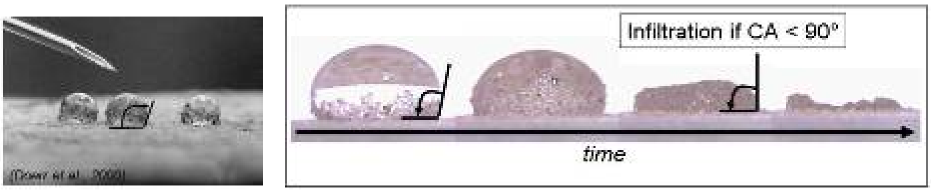


Figure 3.1.3. (a) The contact angle is a measure of the degree of soil water repellency (SWR). (b) The persistence of SWR is measured with the water drop penetration time test.

SWR is a transient soil property: eventually, water ponding on a hydrophobic soil surface will infiltrate into the soil. The time it takes for a water drop to infiltrate into a soil is the ***persistence of SWR*** (Figure 3.1.3b). It can be assessed on field-moist samples for the actual SWR present in the fresh soil material or on dried samples for the potential SWR (Dekker and Ritsema 1994). The persistence of the actual SWR is measured in the laboratory with the water drop penetration test (WDPT) (King 1981a). In essence, the time it takes for a droplet of water placed onto the soil surface to infiltrate completely into the soil is recorded. Bisdom *et al.* (1993) proposed a threshold of five seconds to differentiate between wettable and water-repellent soils. This threshold is arbitrarily chosen and has no physical meaning.

Dekker & Jungerius (1990) introduced seven categories for the persistence of SWR: class 0, wettable; class 1, slightly persistent SWR (5 - 60 s); class 2, strongly persistent SWR (60 - 600 s); class 3, severely persistent SWR (600 s - 1 h); and extremely persistent SWR (>1 h), further subdivided into class 4 (1 - 3 h), class 5 (3 - 6 h), and class 6 (>6 h).

The third criterion needed to fully describe SWR of a soil is the soil-specific ***critical soil water content***. It has been introduced by Dekker & Ritsema (1994) as a soil water content below which the soil is water repellent and above which a soil is wettable. It links to the transient character of SWR and answers the question under which conditions SWR starts and ends. SWR is only expressed when a soil dries out below its site-specific soil water threshold. The relevance of this is illustrated in Figure 3.1.4: the higher the critical soil water content, the longer will be the period with soil water repellent soil conditions. The concept of the critical soil water content has been extended to the 'critical soil moisture zone' by Dekker *et al.* (2001b): Above a certain water content the soil is always wettable. The zone between the two threshold water contents, in which the soil can be wettable or water repellent, is the critical soil moisture zone.

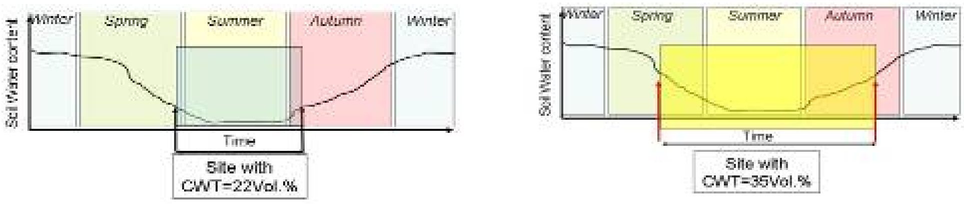


Figure 3.1.4. *Duration of soil water repellency in a soil with a critical water threshold (CWT) of 22% (left) and in a soil with a CWT of 35% (right).*

3.1.4 Origin of SWR

SWR has been described in more than 50 countries (Dekker *et al.* 2005). It occurs in soils of different texture, land use, and a variety of climatic conditions (DeBano 2000; Doerr *et al.* 2006b; Doerr *et al.* 2000a; Woche *et al.* 2005). SWR is caused by natural soil organic matter (SOM). SOM either covers the mineral grains as thin coatings (Bisdom *et al.* 1993), or exists as particulate organic matter (Franco *et al.* 2000), reducing potentially in both cases the wettability of the soils. In general for SWR, the input of organic materials to a soil system and the biological activity in a soil are important (Figure 3.1.5). Reduced soil biological activity is accompanied by a limited decomposition of organic material. These two factors can lead to the accumulation of hydrophobic SOM resulting in SWR. The soil's biological activity is dependent on many factors that are influenced by land use, site management, climate and soil and site conditions (Figure 3.1.6).

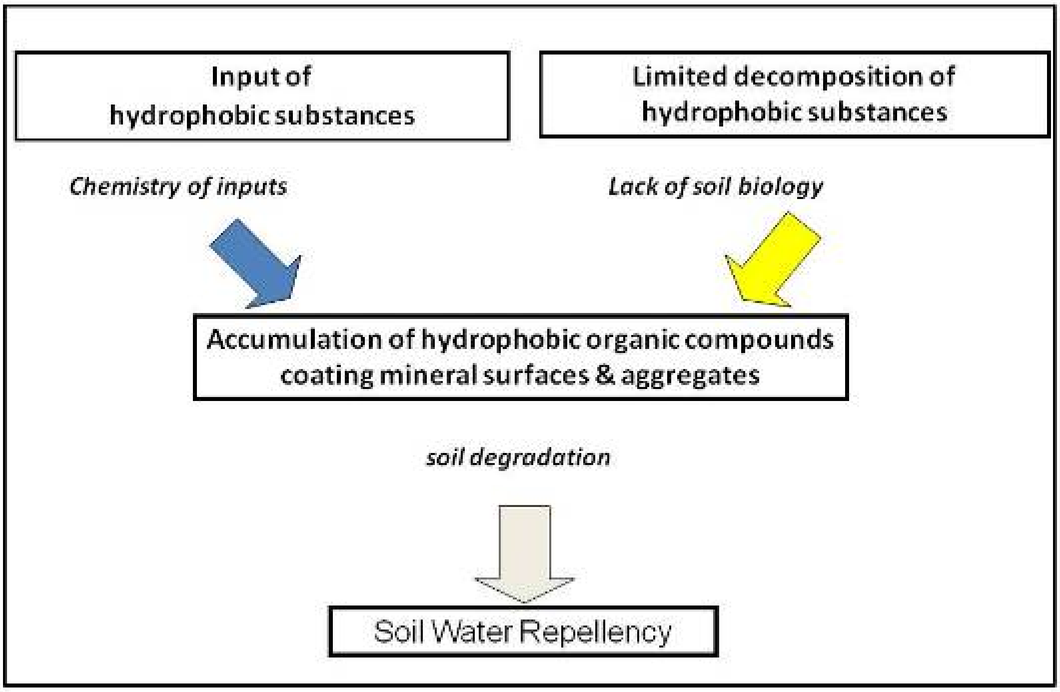


Figure 3.1.5. Why soils become soil water repellent.

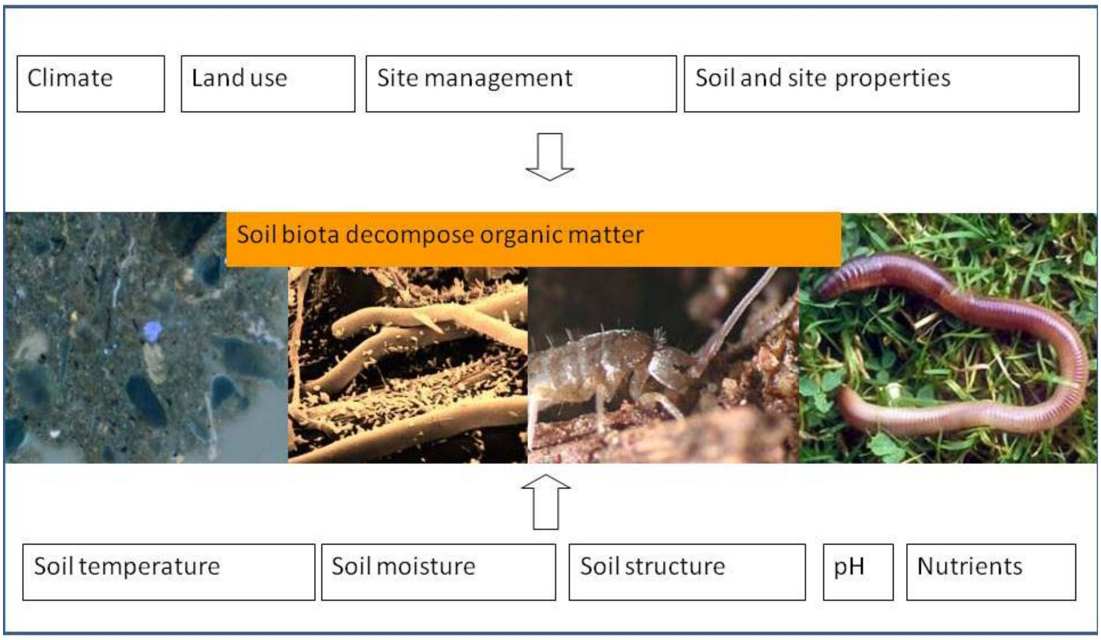


Figure 3.1.6. Decomposition of soil organic matter by soil organisms.

3.1.5 SWR and soil organic matter

Attempts to find correlations between total soil organic matter (SOM) content and SWR showed inconsistent results: some studies found positive correlations (Mataix-Solera and Doerr 2004), others negative correlations (Teramura 1980), while in some studies no correlation was found (Doerr *et al.* 2006b). Preliminary results of our recent survey on the occurrence of SWR under pasture and different soil orders on the North Island, for example, showed a weak positive correlation between organic carbon content and the degree of SWR (Figure 3.1.7). These inconsistent results show that the quantity of SOM is not a reliable predictor of SWR. On the one hand, not all organic carbon compounds are hydrophobic. On the other hand, soils containing hydrophobic substances do not necessarily express SWR. The quality of SOM, thus, has been recognized as an important contributing factor for causing SWR (Wallis and Horne 1992).

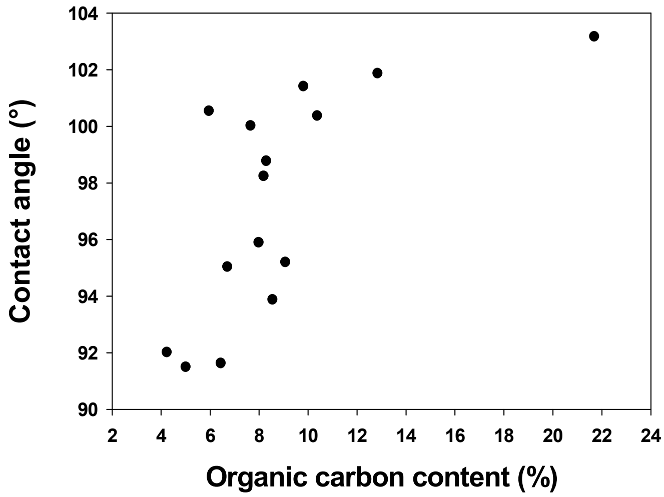


Figure 3.1.7. Positive correlation between organic carbon content and the contact angle for 16 pastoral sites under different soil orders from various regions of the North Island, New Zealand. Discarding the outlier (22% organic carbon content) the R^2 is 0.53 and including it the R^2 is 0.49.

In order to identify chemical compounds causing SWR, many laboratory studies have been carried out (Doerr *et al.* 2005; Horne and McIntosh 2000; Mas'hum *et al.* 1988). The most important generic chemical classes assumed to cause SWR are ***aliphatic hydrocarbons*** and ***amphiphilic molecules***.

In the group of **aliphatic hydrocarbons**, alkanes are the main suspects (Ma'shum *et al.* 1988; Savage *et al.* 1972). Biogenic sources of aliphatic hydrocarbons are, for example, plant waxes and microbial exudates (Franco *et al.* 2000). Capriel et al. (1995a) measured the content of hydrophobic C–H groups in soil organic matter using a reflectance Fourier transform infrared spectrometer (DRIFT) and found a linear relationship between the amount of aliphatic soil extract and the area of alkyl C–H peak at 3000–2800 cm^{-1}. The measurement of hydrophobic C–H groups has also been applied to determine aliphatic carbon which may be responsible for SWR. Ellerbrock et al. (2005) used infrared spectroscopy to indicate the amount of hydrophobic and hydrophilic functional groups in relation to SWR and found that the greater ratio of hydrophobic to hydrophilic groups indicates greater SWR. Doerr et al. (2005) conducted the DRIFT analyses on soils with different hydrophobicity and concluded that the amount of aliphatic C–H in soil material does not determine the SWR of a soil.

Amphiphilic molecules are compounds with strongly polar and strongly non-polar groups. Examples for this chemical class are long-chained fatty acids, salts and esters of fatty acids (Graber *et al.* 2009; Horne and McIntosh 2000; Ma'shum *et al.* 1988).

The first step for identifying compounds causing SWR has generally been the isolation and the removal of the organic material from the soils. Various different extraction procedures including shaking of soil samples, column techniques and Soxhlett extraction with different mixtures of solvents, were applied and their relative efficiencies discussed. Most of the extraction procedures showed no differences in amount of hydrophobic extractable compounds between wettable and repellent samples (Horne and McIntosh 2000); (Mainwaring *et al.* 2004); (Doerr *et al.* 2005; Morley *et al.* 2005). In contrast, Morley *et al.* (2005) and Mainwaring *et al* .(2004)

found a greater abundance of high molecular mass polar compounds in the water repellent samples which were essentially absent in wettable samples. Wettability of acid washed sand was modified in the same manner by extracts of wettable as well as by extracts of repellent sands (Horne and McIntosh 2000). Furthermore, alternating extraction with polar and non-polar solvents led to marked fluctuations in repellency (Horne and McIntosh 2000). These and comparable results suggest that SWR is determined by the composition and nature of the outermost layer of organic material rather than by the characteristics of the bulk of the organic matter (Horne & McIntosh, 2000). Based on their experiments, Horne and McIntosh (2000) suggested four mechanisms for the development of SWR:

(1) ***Changes in the arrangement of molecules***: amphipathic compounds may change their orientation under wettable or dry conditions;

(2) ***Changes in the arrangement of functional groups***: SWR may vary according to the ionisation status of carboxylic groups in amphipathic compounds. If protonated, this functional group will be hydrophobic in character: upon ionisation, the resultant charged carboxylate group will be mostly hydrophilic. The ionisation form of the carboxylic groups will be dependent on moisture content and on soil pH;

(3) ***Hydration of organic compounds***: the screening of hydrophobic compounds will depend on the soil moisture status;

(4) ***Extraction and/or addition of compounds***, be they water-soluble or lipid, may change SWR (Doerr *et al.* 2005; Horne and McIntosh 2000).

The molecular basis of SWR is still poorly understood. Current research questions include:

- Does the occurrence of particular compounds cause SWR?
- Is the relative abundance of compounds causing SWR?
- Is the arrangement of organic compounds important for SWR?

Furthermore, Diehl (2009) showed that SWR is subject to numerous antagonistically and synergistically interacting environmental factors. The influence of different factors including soil pH, water content, drying temperature and wetting temperature were investigated for two contrasting sites in Germany. Her results showed that the interactions of the analysed factors were site-specific. While at one site chemical reactions were necessary for the wetting process, at the other site the amphiphilic substances played a key role together with pH and ionic strength of the soil solution.

3.1.6 Origin of hydrophobic organic substances in soils

The sources of hydrophobic substances are summarised in Figure 3.1.8. The origin of SOM is mostly plant derived such as from roots or plant tissues, plant-derived waxes or organic acids, fungal hyphae or microbial organic acids and polysaccharides.

Vegetation as source of hydrophobic substances

Hydrophobic compounds in SOM may derive directly from the decomposition of plant leaves that contain considerable amounts of waxes, aromatic oils, resins and other hydrophobic compounds. Accordingly, SWR has been associated with certain plant species including for example *Pinus* spp. *Eucalyptus* spp., *Quercus* spp., and *Vaccinuum* spp. (Doerr *et al.* 2000a; Ferreira *et al.* 2000; Mataix-Solera and Doerr 2004). Moreover, certain grass species and legumes such as for example *Agrostis* spp., *Trifolium subterannum*, *Medicago sativa* seem to promote SWR which might be explained by specific plant-microbial community associations (DeBano 2000). Another important plant-derived source of hydrophobic compounds in SOM may be the accumulation of hydrophobic organic acids released as root exudates. The reason for some root exudates to be hydrophobic is their allelopathic functions like, for example, suppressing the germination of competing vegetation.

Microbial organisms as source of hydrophobic substances

A second important source of hydrophobic substances is the soil's microbial community. The decomposition of organic litter by microbial organisms may lead to hydrophobic substances *(McGhie & Posner, 1981).* Furthermore, fungal or microbial by-products as well as exudates can be hydrophobic (Hallett and Young 1999; Urbanek *et al.* 2007).

Fire as source of hydrophobic substances

Finally, fire has been identified as a major source of SWR (Mataix-Solera and Doerr 2004; McGhie and Posner 1981; Robichaud and Hungerford 2000). Suggested mechanisms are the volatilisation of hydrophobic organic substances and the subsequent concentrated condensations in cooler soil layers. SWR depends on the temperature of the fire, the pre-fire moisture conditions and the amount and quality of the litter burnt. Fire-induced SWR might play an important role in New Zealand as many pastoral sites were established after burning down the native bush. No study has so far examined the role of fire on SWR in New Zealand.

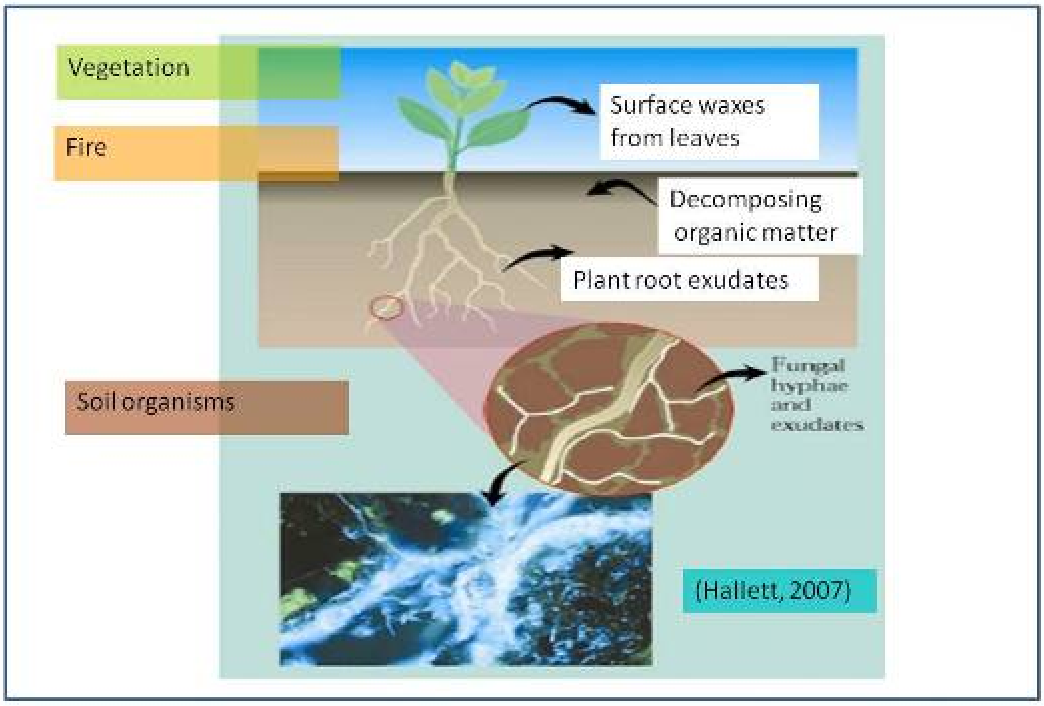


Figure 3.1.8. Sources of hydrophobic substances in soil water repellent soils.

3.1.7 Consequences of SWR - Reduced water infiltration rate into soils

Description

SWR reduces the rate of water infiltration into soils. In a hydrophilic soil, water infiltrates across the entire cross section of the soil surface, and the rate of infiltration is limited by the soil texture (e.g., higher in coarse textured soils) or by an unfavourable (e.g., compacted) soil structure. In soils where SWR occurs, water typically infiltrates across only a fraction of the soil surface (see Figure 3.1.9). The reduction of infiltration rates by SWR can be directly measured by comparing the infiltration rates of water with those of ethanol (Figure 3.1.9). Ethanol infiltration is not influenced by SWR.

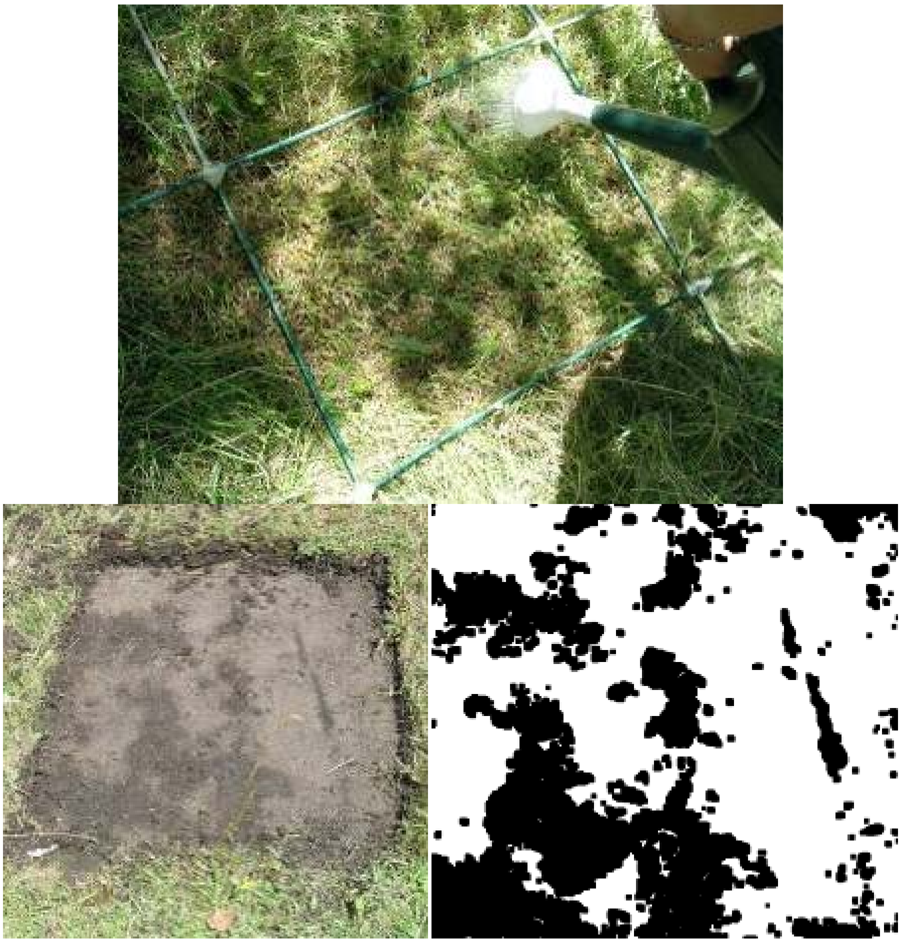


Figure 3.1.9. **Top**: Application of 20 l/m^2 water to a pasture with a hydrophobic soil. **Bottom**, **left**: Infiltration pattern at 2 cm soil depth. The dark areas represent the areas of the soil that were wetted during the infiltration event. **Right**: The wetted areas indicate the fraction of the soil surface across which water infiltrated. This area was about 40% of the total experimental area.

Explanation

Two forces control water infiltration and drainage: capillarity associated with the nooks and crannies of the soil's porous networks, plus gravity which attracts water downwards towards the centre of the Earth. As a rule of thumb, in hydrophilic soils, flow in fine-textured and in very dry soils is dominated by capillarity, and for coarse-textured and wet soils the dominant force is gravity and can be approximated by the hydraulic conductivity.

SWR leads to a reduction (for CA <90°), or total loss (CA =90°) of capillarity irrespective of soil texture. As a consequence, in hydrophobic soils (CA >90°), it is necessary for water to pond up to a certain ponding height above the soil surface, before it can infiltrate (see Appendix 1 for a theoretical explanation). In this situation, water infiltrates first into the pores with the largest diameter, the macro-pores, and subsequently results in the preferential flow of water and solutes.

Literature review

The ***reduction of the water infiltration rate by SWR*** is well documented in many studies (Clothier *et al.* 2000; Dam *et al.* 1990; De Bano 1975; DeBano 1971; Imeson *et al.* 1992; King 1981b; Lamparter *et al.* 2006; Wallis *et al.* 1990b; Wallis *et al.* 1991; Wang *et al.* 2000). The reduction of the water infiltration rate into water repellent soils in the literature ranged from a factor of six (Wallis *et al.* 1990b) up to 25 (DeBano 1971) when compared to a hydrophillic control soil.

Key research gaps

Currently, there are no experiments that confirm theoretical models (Bachmann *et al.* 2007; Deurer and Bachmann 2007) of the time-dependency (e.g. seasonality) of reduced infiltration rates into soils with SWR.

3.1.8 Consequences of SWR - Increased surface run-off and overland flow, plus the generation of floods and erosion

Description

SWR most often occurs in the topsoil (Figure 3.1.10, A), but a soil layer with SWR can also be sandwiched between a wettable top- and subsoil (Figure 3.1.10, B). Accordingly, there are two possible scenarios of how SWR influences run-off and overland flow.

Scenario A (Figure 3.1.10, A):

SWR reduces the infiltration rate at the soil surface. If the rainfall rate exceeds the infiltration rate, water ponds on the water repellent soil surface, runs off and generates overland flow. Downslope overland flow can be diverted into macro-pores and cracks and be transferred into the subsoil. Therefore, the density of macro-pores and cracks determines whether overland flow is widespread or remains a local phenomenon.

Scenario B (Figure 3.1.10, B):

Rainfall can readily infiltrate into the hydrophilic topsoil. The water repellent subsoil acts like a brake on the infiltration front that moves vertically downward through the soil. The water starts to pond at the interface between topsoil and water repellent subsoil. If the topsoil is highly permeable then the water will flow laterally, and often preferentially downslope. The lateral flow of water along the interface of the water repellent subsoil can be diverted into macro-pores and cracks through the water repellent subsoil. Again, like for scenario A, the density of macro-pores and cracks determines whether the lateral flow is widespread or remains only a local phenomenon. If the topsoil is less permeable, then the topsoil will saturate and eventually saturation-excess overland flow will start.

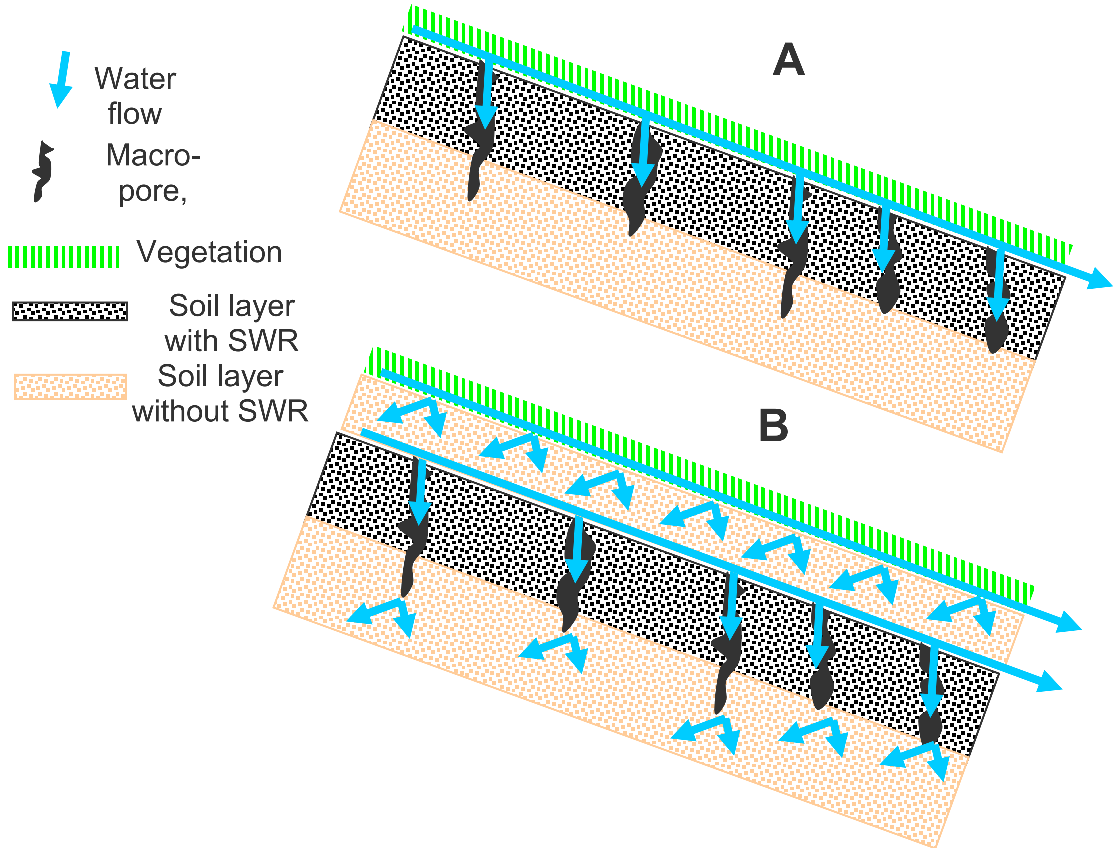


Figure 3.1.10. Schematic illustration of water flow on grassed hillslopes with soils suffering from SWR. **A** Scenario with a topsoil layer with high SWR and a wettable subsoil. **B** Scenario with a layer with high SWR sandwiched between a wettable top and subsoil. The figure was modified from (Doerr *et al.* 2000b).

Explanation

Whenever the rate of rainfall exceeds the rate of infiltration, excess water accumulates on the soil surface. Excess water is collected in surface depressions forming puddles. Only when the surface storage is filled and the puddles overflow, surface run-off starts. Surface run-off typically starts as sheet flow, and as it accelerates, it gains in erosive power and can create channels. The smallest channels are termed rills. Once the small streams merge with one another, they form gullies.

Three typical stages of erosion on a water repellent hillslope according to Scenario B (Figure 3.1.10) can be defined (De Bano 2000). (1) During rainfall, the wettable topmost surface soil layer becomes saturated leading to a decreased shear strength. (2) The surface soil layer begins to slide downslope and a miniature debris flow channel (rill) develops. (3) Water in the wettable topsoil adjacent to the developing rill flows into the debris flow channel. Water in the developing rill now erodes sediment first from the water repellent soil and subsequently from the wettable subsoil underneath it. However, once the rill reaches the wettable subsoil and infiltration increases, the flow in the rill decreases and also its erosive power.

Literature review

Surface run-off and overland flow

- Many studies have shown that surface ***run-off and overland flow generally increase with an increase in SWR*** (Burch *et al.* 1989; Buttle and Turcotte 1999; Frasier *et al.* 1998; Gomi *et al.* 2008; Keizer *et al.* 2005; Leighton-Boyce *et al.* 2007; Miyata *et al.* 2009; Pierson *et al.* 2009; Scott and Van Wyk 1990; Valeron and Meixner 2010; Walsh *et al.* 1994). A majority of the studies focused on the impact of forest fires (Fig. 3.1.11 and 3.1.12). Estimates for the ***increase in run-off and overland flow by SWR ranged from three*** (Burch *et al.* 1989) ***to 16 times*** (Leighton-Boyce *et al.* 2007).
- Most studies have used an indirect method to attribute the increase of run-off to an increase in SWR. This means, for example, they have statistically correlated run-off and SWR. One study has ***measured the impact of SWR on run-off directly*** by comparing

the results when either water or water plus a surfactant was used in simulated rainfall experiments (Leighton-Boyce *et al.* 2007). They found, for example, that overland flow on a recently burnt hillslope with SWR was 16 times higher when water instead of water plus surfactant was used.

- At a similar rainfall rate the ***run-off rate depends on the degree of SWR***. For example, a study analysing the temporal dynamics of run-off on forested hillslopes in Portugal found that run-off at times of strong-to-extreme SWR was significantly higher than when SWR was none-to-slight (Keizer *et al.* 2005; Pierson *et al.* 2008).
- The between-year variability in run-off and infiltration in soils with SWR was assessed in several burned and unburned sagebrush systems. The large variability indicated that ***the influence of SWR on run-off generation is quite variable*** and its impact might be masked by short-term fluctuations in its strength (Pierson *et al.* 2008).
- ***SWR decreases the filtering effects of vegetation*** for run-off and erosion both on hillslopes (Pierson *et al.* 2009), and in riparian buffer strips (Frasier *et al.* 1998).
- ***Upscaling*** plot-scale run-off experiments to the scale of entire catchments is ***not necessarily straightforward***. For example, run-off can be much more pronounced at the plot compared with the catchment scale (Doerr *et al.* 2003). An explanation could be the increased capture of locally generated overland flow at the catchment scale by bypass route-ways that are under-represented at plot-scale (Doerr *et al.* 2003). The larger the spatial connectivity of run-off source areas suffering from SWR, the larger will be the hillslope or catchment scale overland flow (Huffman *et al.* 2001; Johansen *et al.* 2001).
- The ***vegetation and soil surface cover*** such as a layer of wettable needle litter or ash ***can mitigate the impact of SWR*** on run-off and overland flow (Cerda and Doerr 2008; Gomi *et al.* 2008; Miyata *et al.* 2009).

Figure 3.1.11. Overland flow transporting burnt soil and charred debris during intense rain following a wildfire in a eucalypt forest in the Victorian Alps with water-repellent soils, south-eastern Australia in 2003. The figure was taken from (Shakesby and Doerr 2006).

Generation of floods

- ***Flooding*** is a complex process that is triggered by a multitude of site-specific and climatic conditions. A study investigating the cause of increased flooding in forested catchments in Northern Germany found a low infiltration rate to be the key problem. The latter was attributed to a combination of SWR, soil texture and a poor macro-porosity (Wahl *et al.* 2005).
- In a catchment suffering from SWR, overland flow for individual storms measured at the plot scale was generally higher during dry periods than wet periods, suggesting that water repellency reduced the infiltration rate. However, catchment scale stormflow was highest during wet periods. The authors concluded that for the particular catchment stormflow was governed by subsurface rather than overland flow (Miyata *et al.* 2010).
- ***Burnt catchments*** often suffer from SWR and generally respond quickly to rainfall, producing more flash floods than in comparable unburnt catchments or in the same catchment prior to burning (Shakesby and Doerr 2006). ***Water-repellent bare soils*** and loss of plant and litter cover tend to cause the ***flood peak to arrive faster as well as being higher*** (Neary *et al.* 2003; Scott 1993; 1997).

Erosion

- ***The influence of SWR on generating erosion*** depends, like the generation of overland flow and flooding, on the degree of contiguity of the hydrophobic surface (Shakesby *et al.* 2000). For example, a study (Booker *et al.* 1993) analysed overland flow and erosion on burnt hillslopes in California. Where cracks and macro-pores through the hydrophobic surface soil were lacking overland flow and slopewash-induced erosion increased, and where they existed, the slopes were prone to landslides because of the increased transfer of water into the subsoil.
- A few studies have directly measured that with increased run-off and overland flow at sites with SWR also ***erosion*** increases (Gomi *et al.* 2008; Miyata *et al.* 2009; Pierson *et al.* 2009).
- ***SWR*** reduces the water sorptivity of soil aggregates. Consequently, dry soil aggregates are less prone to destruction by slaking, and their aggregate stability is improved. The latter ***can also increase the resistance of soil to erosion*** (Capriel *et al.* 1995b; Giovannini and Lucchesi 1983; Rawitz and Hazan 1978).

Figure 3.1.12. Rill erosion on a steep and water-repellent slope. The photo shows rills formed after the Buffalo Creek Fire in May 1996, south-west Denver, Colorado, USA. The figure was taken from Shakesby and Doerr (2006)

Key research gaps

Currently, there are no experiments quantifying directly the impact of SWR on the run-off and overland flow of nutrients and contaminants. For example, for New Zealand, it is not clear how important SWR is for P-losses from hill-country pastures to surface waters.

More studies for a better understanding of upscaling the results from small-scale plot experiments of SWR induced run-off, overland flow and erosion to the catchment scale are needed.

3.1.9 Consequences of SWR - Less water storage

Description

In soil layers suffering from SWR, water from rainfall or irrigation either runs off or infiltrates into them in the form of fingers or channels (Fig. 3.1.13). Consequently, water in water repellent soil layers is (re-) distributed unevenly (Fig. 3.1.13), and such layers store less water than if they were hydrophilic. However, water that is routed through fingers and channels in the water repellent layer can be stored in the underlying wettable soil layers, and by this mechanism, increase the water storage in the subsoil.

Figure 3.1.13. Uneven water storage in soil profiles with SWR. **Left**: Wetting pattern of the soil surface (view from the top) after a two-hour water infiltration experiment. **Right**: Wetting pattern after a large rainfall event (75 mm in 3-4 h). The photo was taken from (Doerr *et al.* 2000b).

Explanation

The forces that are responsible for the homogeneous (re-)distribution of water in three dimensions are capillarity and gravity. SWR greatly reduces or abolishes capillarity, but does not affect gravity (see Appendix 1). In a water repellent dry soil, gravity dominates water flow, and water at the soil surface preferably infiltrates into macro-pores or cracks (see Appendix 1 for an explanation) causing fingered or preferential flow through the water repellent layer.
The lack of capillary forces in water repellent soils can be measured in the form of the sorptivity. At the smallest spatial scale, the sorptivity of water into a soil aggregate is quantified (Fig. 3.1.14). The cumulative infiltration I [mm^3/mm^2] (Fig. 3.1.14) of water or ethanol into a soil aggregate is proportional to the sorptivity, S [mm/s$^{0.5}$]. Sorptivity is a function of the liquid saturation at the start, θ_i , and the end, θ_0 , of the experiment. For early times of the infiltration process the cumulative infiltration can be estimated from (Philip 1957):

$$I = S(\theta_0, \theta_i)\sqrt{t}\ ,$$

where t [s] is time. S can be estimated as the slope of I versus the square root of the time. Sorptivity is "essentially a measure of the capacity of the medium to absorb or desorb liquid by capillarity" (Philip 1957).

The reduction in sorptivity by SWR can be measured directly by comparing the sorptivity of ethanol and water. Corrected for the different fluid properties (e.g. viscosity) the ratio of the two is termed the 'repellency index'(Tillman 1989). The larger the ratio, the larger is the sorptivity of ethanol compared with water, and the more water repellent is a soil.

We measured the sorptivity of water and ethanol into macro-aggregates (> 4.75 mm diameter) of a water repellent and hydrophilic silt loam soil (Fig. 3.1.14). The sorptivity of water in the hydrophobic soil was two orders of magnitude smaller than for ethanol.

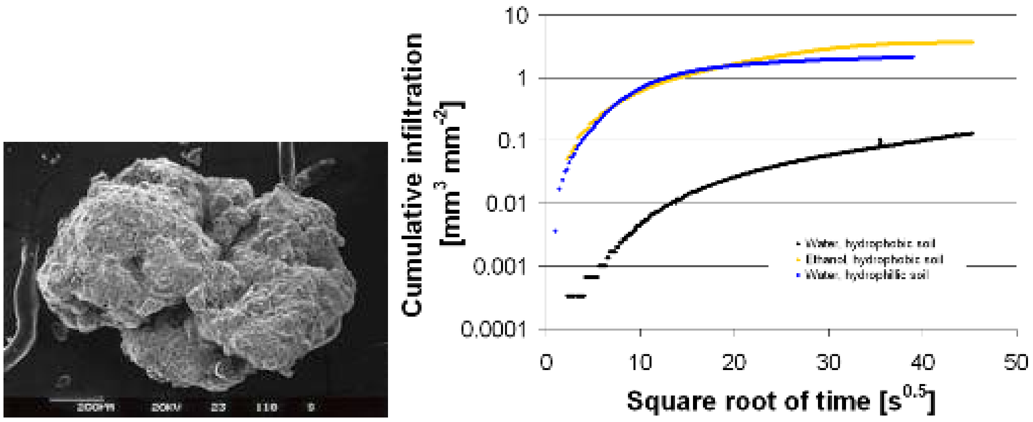


Figure 3.1.14. Water storage at the scale of soil aggregates. **Left:** Electron micrograph of a soil macro-aggregate. [http://www.abc.net.au/science/features/soilcarbon/; last accessed 12.04.2010]. The photo was taken by A McBratney. **Right**: Absorption of water and ethanol (= cumulative infiltration) by macro-aggregates from a silt loam soil with and without SWR. The macro-aggregates had the same initial soil moisture content. Note the logarithmic scale of the Y-axis for cumulative infiltration; the sorptivity of water in the hydrophobic soil is two orders of magnitude smaller than for ethanol. The sorptivity is equivalent to the slope of the cumulative infiltration in the early phase of infiltration.

Literature review

- With current methods, the ***sorptivity*** of disturbed soil (Clothier et al. 1983), of undisturbed soil (Cook and Broeren 1994), and of one up to a few large soil aggregates (Gerke and Köhne 2002; Leeds-Harrison *et al.* 1994) can be measured and the impact of SWR on sorptivity can be quantified by comparing ethanol and water (Tillman 1989).
- The ***water storage capacity*** (Doerr *et al.* 2006a) of very repellent soils was considerably less than for comparable wettable soils. Wetting rate assessment of 100 cm^3 intact soil cores using continuous water contact at -20 mm pressure head over a period of seven days showed that, irrespective of texture, severe to extreme SWR persistence significantly reduced the maximum water content below that of comparable wettable soils.
- ***Irregular (re-)distribution of soil moisture in water repellent soil layers*** at the soil profile scale. For example, differences in volumetric water contents of up to 28 Vol% on a decimetre scale in soils with a water repellent layer of a sandy or a clayey texture were measured (Dekker and Ritsema 1996). Such variability prevents homogeneous water storage (Greiffenhagen *et al.* 2006). For example, in simulated rainfall experiments on volcanic soils under different land use in Mexico, shallow and irregular wetting fronts were observed in water-repellent soil layers reducing soil water storage capacity near the soil surface (Jordan *et al.* 2009).
- A strongly water-repellent surface layer with preferential channelling of water through cracks and macro-pores can lead to a dry surface soil and a ***higher soil moisture storage in the subsoil*** (Burch *et al.* 1989; Imeson *et al.* 1992). A water repellent topsoil can additionally prevent evaporation and capillary rise of water from the sub to the topsoil (Imeson *et al.* 1992). Higher soil moisture storage in the subsoil can be a competitive advantage for vegetation. SWR under trees transferred the water into the subsoil, out-competing shallower rooted annual grasses for water (Robinson *et al.* 2010).

Key research gaps

Currently, we cannot predict the seasonal water storage in soil layers suffering from SWR based on easily measurable soil properties.

3.1.10 Consequences of SWR - Less pasture and crop growth

Description
Uneven soil moisture distribution and less water storage in the topsoil lead to less and often patchy pasture growth. For cropping on soils with SWR the main issue is the establishment of the crop. The uneven soil moisture distribution in the topsoil leads to patchy germination and emergence of the crop.

Explanation
The uneven soil moisture distribution is a result of the interaction of the topography and the spatial distribution of SWR and macro-pores at the site. For example, on a hillslope water runs off from areas affected by SWR and with few macro-pores, and is transferred to the downslope areas. On flat areas that suffer from SWR water can run off into (micro-) depressions where it is stored, and there it promotes localised pasture growth (Fig. 3.1.15). This becomes especially obvious after prolonged droughts and where pastures or crops are not irrigated (Fig. 3.1.15). A connection between the Dry Patch Syndrome in pasture and the occurrence of SWR was shown recently for the Maraetotara district in Hawke's Bay. Across a pasture, a mosaic of patches with less pasture growth ('Dry patches') occurred (for more details see Section 3.3). Currently, the pasture production and temporal variability of SWR within and outside dry patches is being measured in an AGMARDT funded postdoctoral fellowship project (Fig. 3.1.16). First results show significantly less pasture growth within than outside the patches (Fig. 3.1.16). In the turfgrass industry, the 'Dry Patch Syndrome' is known as the 'Localised Dry Spots' syndrome and it is known to be related to SWR (Kostka 2000).

Figure 3.1.15. Non-irrigated fairway suffering from SWR on the Cambridge golf-course at the end of summer after a prolonged dry period. The grass growth is sustained only within the depressions into which water run-off is stored and can be taken up by the pasture (marked by blue arrows). The fairways at the Cambridge golf-course are not irrigated.

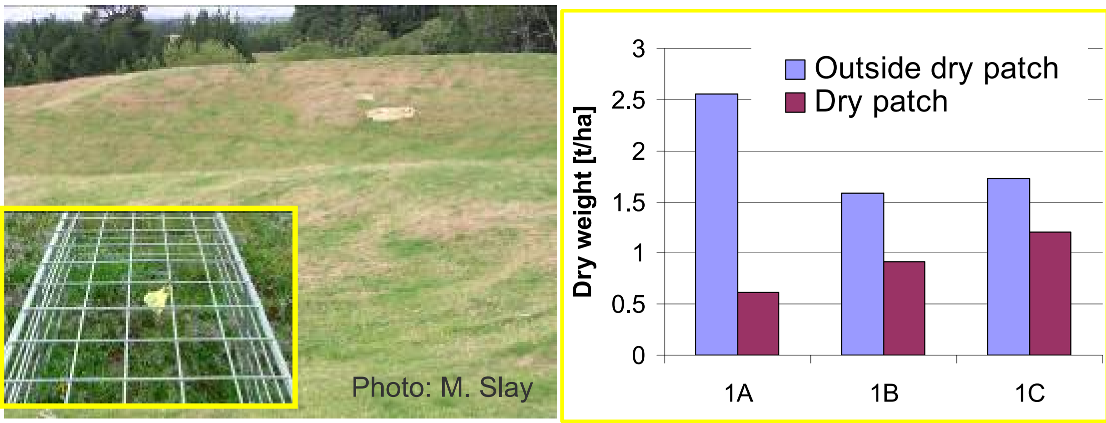


Figure 3.1.16. **Left**: Pasture near Ashley-Clinton suffering from the Dry-Patch-Syndrome (DPS). The soils under the dry patches have a higher degree of SWR than outside of them. The pasture production at a site suffering from DPS for January 2010 that was measured with cages (see inset photo on the left) in the Maraetotara district in Hawke's Bay. **Right:** The pasture

production at three patches labelled 1A, 1B, and 1C was significantly lower within than outside a dry patch. The patches occurred at the same locations for at least the last five consecutive years.

Literature review

- Many soils in Western and Southern Australia suffer from severe SWR. ***Crop and pasture establishment*** (e.g., germination and emergence) on sites suffering from SWR is very difficult. For ***barley***, the application of banded wetting agent while furrow seeding with press wheels increased seedling emergence by 55%, dry matter production by 43% and grain yield by 33%, despite more weeds occurring (Crabtree and Gilkes 1999a). For ***pasture***, the use of a wetting agent plus press wheels increased seedling emergence by 77%. Early pasture production increased six-fold. The wetting agent had a large residual effect on pasture composition applied two years previously. For example, the proportion of subterranean clover increased from 6 to 33% when the wetting agent was used (Crabtree and Gilkes 1999b).
- Water repellent sand pastures contain ***little, if any legumes***. In wide areas of South Australia amelioration of SWR for example by clay spreading generally doubles cropping yields (Cann 2000).
- In a field experiment on sandy soils with SWR in New Zealand pasture, establishment was significantly higher when a ***wetting agent*** was applied at seeding (Wallis *et al.* 1990a).

Key research gaps

Currently, we cannot predict the impact of SWR on seasonal and annual pasture production and pasture composition.

3.1.11 Consequences of SWR - Preferential flow of water and solutes

Description

Water and solutes do not readily and homogeneously flow through a water repellent soil layer. Instead, they form distinct flow channels and fingers (Fig. 3.1.18), and they are the typical signature of preferential flow. Once water and solutes have passed through the water repellent soil layer and enter a wettable soil layer, the degree of preferential flow usually slowly decreases (e.g., the width of the preferential flow channels increases).
A water repellent soil layer can occur in the topsoil layer, but also in the subsoil. Consequently, water-repellency- induced preferential flow can start near the soil surface or in the subsoil. Also, in most soils SWR, and likewise water-repellency-induced preferential flow occurs only once the soils dry out below a critical water content threshold, for example in a period ranging from summer to early autumn.

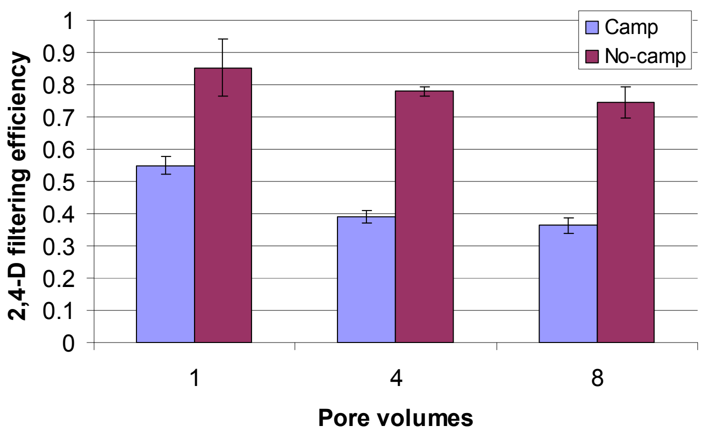


Figure 3.1.17. Preferential flow of the herbicide 2,4-D in the top 10 cm of a soil suffering from SWR under pasture near Hamilton. The filtering efficiency describes the fraction of the herbicide retained in the soil volume as a function of drainage represented here as pore volumes. For example, if 100% of 2,4 D is retained in the soil, then the filtering efficiency is 1.0. At this pastoral site, camp sites with 8% soil organic carbon content were extremely hydrophobic with a contact angle of about 101°, and no-camp sites with 5% soil organic carbon content were

moderately hydrophobic with a contact angle of about 95°. The filtering efficiency of the more hydrophobic camp sites was about half of the less hydrophobic no-camp site. One pore volume for the camp site equals a drainage volume of about 50 mm and for the non-camp site of about 60 mm. The graph shows unpublished results from an AGMARDT funded postdoctoral fellowship of Dr Aslam on the impact of soil organic carbon on the soil's filtering function. More details on the sites and their soil properties can be found elsewhere (Aslam *et al.* 2009a).

The preferential flow of water and solutes leads to less filtering of contaminants, the loss or uneven distribution of plant-nutrients, and a patchy soil water storage. Preferential flow is assumed to be the key mechanism for the transfer of organic contaminants (e.g., pesticides, pharmaceuticals; Fig. 3.1.17), viruses and bacteria into groundwater resources. Irrigation, the application of surfactants or clay, and tillage can reduce or prevent SWR induced preferential flow.

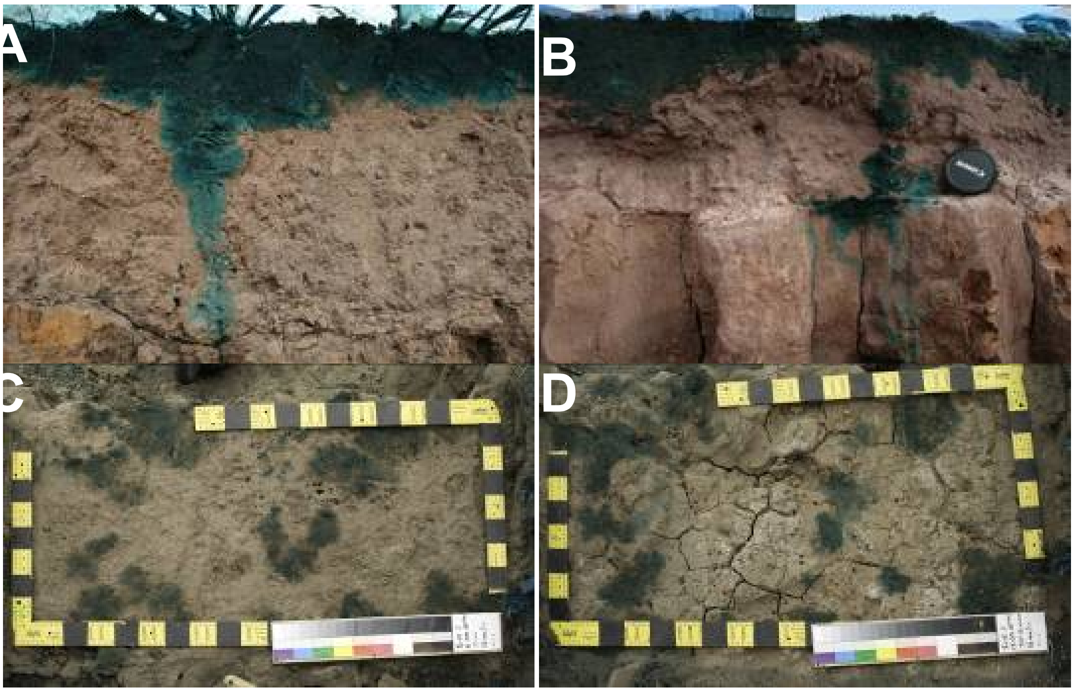


Figure 3.1.18 Preferential flow of a Brilliant Blue dye tracer in a Duplex soil in Tasmania that was triggered by a water repellent layer in the topsoil. The photos are courtesy of Marcus Hardy, and are taken from his PhD thesis on preferential flow in Duplex soils in Tasmania. **A) and B)** Preferential flow channel extending from the water repellent top- into the wettable subsoil. **C)** Top down view on the interface between top- and the first subsoil layer. The dark spots mark preferential flow channels of Brilliant Blue. **D)** Top down view on the interface between the first and second subsoil layer. The dark spots mark preferential flow channels of Brilliant Blue. The second subsoil layer has a very high clay content.

Explanation

The leaching of water and solutes in soils follows the path of least resistance to flow. The higher the combined forces of capillarity and gravity, the smaller is the resistance to flow. In the same soil depth, for example, the soil surface, the gravity forces are equal at any point. The higher the degree of SWR, the smaller will be the soil's capillarity (see Appendix for an in-depth explanation). Therefore, in a soil suffering from SWR, water and solutes preferably flow through channels or parts of the soil that have a lower degree of SWR (= higher capillarity). If the soil is hydrophobic and has no capillarity at all, then water and solutes will pond and then move through the largest pores, the macro-pores, first.

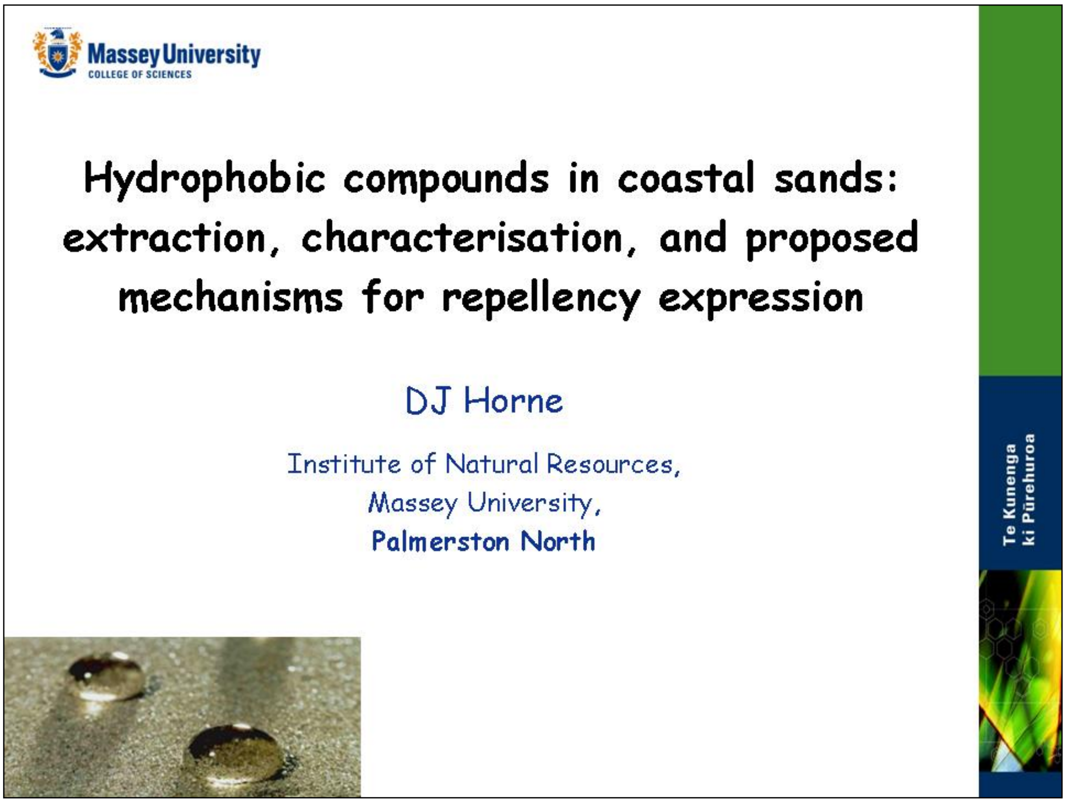
Key literature

- ***Preferential flow*** is the rule rather than the exception in a wide variety of soils and climates, and SWR is one of its causes (Flury *et al.* 1994; Jarvis *et al.* 2008; McLeod *et al.* 2008; Ritsema and Dekker 1996; Ritsema *et al.* 1993; Wang *et al.* 1998).

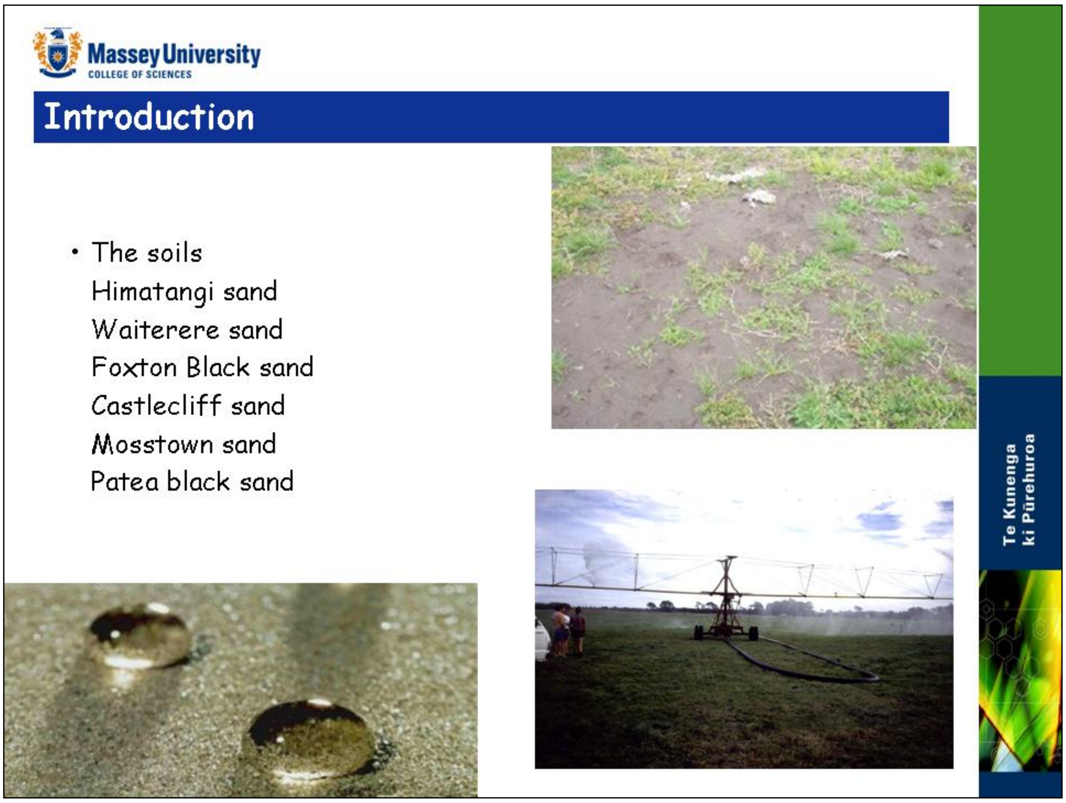
- Long-term application of ***olive mill wastewater*** increases SWR and led to a decrease in infiltration rates and an increase in preferential flow (Mahmoud *et al.* 2010).
- On a former long-term waste water disposal field, sandy soils exhibited SWR and ***preferential channelling of solutes and water mainly in summer when they dry out below a critical water content threshold***. In winter, when the soils were predominantly wettable, preferential flow did not occur (Wessolek *et al.* 2009).
- The ***application of a soil surfactant*** reduced the occurrence of SWR and preferential flow in a sandy soil of a golf course fairway in the Netherlands (Oostindie *et al.* 2008) and the preferential flow of fungicides in a sandy soil of a golf course in Norway (Larsbo *et al.* 2008).

Key research gaps
Currently, we cannot predict when and to what degree SWR-induced preferential flow will occur based on measurable soil properties.

3.2 Hydrophobic compounds in coastal sands: extraction, characterisation, and proposed mechanisms for repellency expression – *D Horne*



3.2.1 Introduction



3.2.2 Methodology

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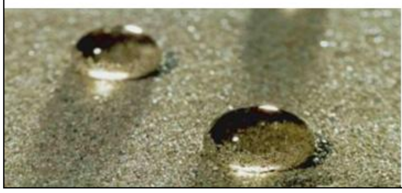
Methodology

- MED measurements
- Soil samples were extracted (columns, shaking, Soxhlet apparatus)
- Separation and analysis of extracts
- Sequential extraction of Himatangi sand
- Addition experiments



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3.2.3 Characterization of the degree of soil water repellency

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Initial values for MED

- There soils varied in the severity of repellency expression
- There was little change in MED values if samples were pre-heated

The MED value of soils and the effect of drying temperature

	MED after drying at:		
Soil	**20 °C (air-dried)**	**70 °C**	**105 °C**
Himatangi sand	2.7	2.8	3.0
Waitarere sand	1.2	1.3	1.4
Foxton black sand	1.2	0.8	1.3
Castlecliff sand	2.1	1.4	1.4
Mosstown sand	0.8	1.4	0.8
Patea black sand	0.8	1.1	0.9

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3.2.4 Extraction of hydrophobic compounds

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Extraction

- All extraction techniques were effective
- The solvent mixtures require a base and an alcohol.
- Better lipid solvents like toluene do not increase the efficiency of extraction.

A comparison of extraction procedures and solvents for lowering the repellency of Himatangi sand (MED 2.8)

Technique and Solvent[a]	MED
a)Shaking	
• chloroform:methanol:water (9:1:1)	2.0
• chloroform:methanol:1M hydrochloric acid (9:9:1)	2.2
• chloroform:methanol:ammonia (10:10:1)	0.8
• toluene:ethanol (2:1)	1.6
a)Column	
• chloroform:methanol:ammonia (10:10:1)	0.2
• isopropanol:ammonia (7:3)	0.4
a)Soxhlet reflux	
isopropanol:ammonia (7:3)	
chloroform:methanol:ammonia (10:10:1)	0
	1.6

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Extraction

A comparison of extraction procedures and solvents for lowering the repellency of Himatangi sand (MED 2.8)

Technique and Solvent[a]	MED
a)Shaking	
• chloroform:methanol:water (9:1:1)	2.0
• chloroform:methanol:1M hydrochloric acid (9:9:1)	2.2
• chloroform:methanol:ammonia (10:10:1)	0.8
• toluene:ethanol (2:1)	1.6
a)Column	
• chloroform:methanol:ammonia (10:10:1)	0.2
• isopropanol:ammonia (7:3)	0.4
a)Soxhlet reflux	
isopropanol:ammonia (7:3)	
chloroform:methanol:ammonia (10:10:1)	0
	1.6

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Extraction

- Although the Soxhlet and column techniques lowered MED to a similar degree, the Soxhlet apparatus removed more material.
- Only 4 hours of Soxhlet extraction is required to eliminate repellency (cf. 16 hours for some Australian soils).
- Even so, you can still remove large quantities of material on further Sohlet extraction.

Quantities of material extracted from Himatangi sand using the column and Soxhlet techniques and an isopropanol:ammonia (7:3 v:v) mixture

Extract Fraction	Technique	
	Column	Soxhlet
Total (mg g^{-1}) Lipid[a] (mg g^{-1}) Polar[b] (mg g^{-1})	2.4 0.8 1.9	5.0 1.8 3.4
MED at conclusion of extraction	0.4	0

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3.3.5 Analysis and interpretation of hydrophobic compounds

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Identifying compounds

- Two types of compounds, lipids and water soluble substances, were extracted.
- Both have a role in repellency.

The effect of drying soils to different temperatures on MED values.

	Units	Castlecliff sand	Mosstown sand	Patea black sand	Waitarere sand	Foxton black sand	Himatangi sand
MED Total carbon Soxhlet-extractable Water-soluble fraction Lipid material Neutral lipids Acidic lipids Polar lipids[a] Not eluted	% mg g^{-1} mg g^{-1} mg g^{-1} mg g^{-1} (%)[b] mg g^{-1} (%) mg g^{-1} (%) mg g^{-1} (%)	2.0 0.8 1.7 0.9 0.6 0.10 (17) 0.12 (20) 0.15 (25) 0.23 (39)	0.5 2.1 1.5 0.8 0.9 0.15 (17) 0.18 (20) 0.16 (18) 0.41 (45)	1.1 8.6 5.3 2.9 3.0 0.43 (18) 0.78 (26) 0.87 (29) 0.82 (27)	1.5 0.5 2.5 2.0 0.6 0.20 (33) 0.12 (20) 0.08 (13) 0.20 (33)	1.2 3.5 5.8 4.8 1.7 0.20 (12) 1.30 (76) 0.25 (14) 0 (0)	2.7 4.9 5.0 3.4 1.8 0.3 (17) 0.8 (45) 0.4 (22) 0.3 (17)
Vegetation		Lupins & Dune grass	Pasture	Pasture	Lupins & Dune grass	Pasture	Pasture

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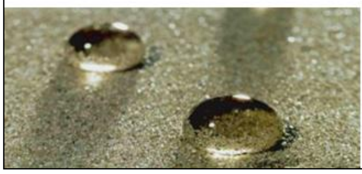
The substances that play a role in repellency

Extracted material

- Lipid fraction
  - Neutral lipids
    Alkane hydrocarbons
  - Neutral lipids
    Humic acids
  - Acidic lipids
    Long chain fatty acids
- Water soluble fraction
  - Hymetamelonic fraction of humic acids



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Quantities of extracted fractions and the relation to MED

- There was no relationship between MED value, soil carbon content or between MED and the quantities of either total lipid or any of the lipid fractions
- MED does not seem to be correlated to the quantity of the water soluble fraction
- Neither is there relation between soil C and the quantity of material extracted.

Carbon content and quantities of fractions extracted from a range of soils.

	Units	Castleclif f sand	Mosstown sand	Patea black sand	Waitarer e sand	Foxton black sand	Himatangi sand
MED	%	2.0	0.5	1.1	1.5	1.2	2.7
Total carbon	mg g^{-1}	0.8	2.1	8.6	0.5	3.5	4.9
Soxhlet-	mg g^{-1}	1.7	1.5	5.3	2.5	5.8	5.0
extractable	mg g^{-1}	0.9	0.8	2.9	2.0	4.8	3.4
Water-soluble	mg g^{-1}	0.6	0.9	3.0	0.6	1.7	1.8
fraction	(%)[b]	0.10 (17)	0.15 (17)	0.43 (18)	0.20 (33)	0.20 (12)	0.3 (17)
Lipid material	mg g^{-1} (%)	0.12 (20)	0.18 (20)	0.78 (26)	0.12 (20)	1.30 (76)	0.8 (45)
Neutral lipids	mg g^{-1} (%)	0.15 (25)	0.16 (18)	0.87 (29)	0.08 (13)	0.25 (14)	0.4 (22)
Acidic lipids	mg g^{-1} (%)	0.23 (39)	0.41 (45)	0.82 (27)	0.20 (33)	0 (0)	0.3 (17)
Polar lipids[a]							
Not eluted							
Vegetation		Lupins & Dune grass	Pasture	Pasture	Lupins & Dune grass	Pasture	Pasture

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3.3.6 Sequential extraction and additional experiments

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Sequential extraction

- Sequential extraction with isopropanol:ammonia mixture and then shaken with ammonia.
- As progressively more material is removed, repellency cycles

Effect of sequential extraction of Himatangi sand (initial MED value = 2.8) on MED values and the quantity of material removed.

Procedure	MED Value	Quantity Extracted (mg g^{-1})
1st IPA[a]	0	1.5
1st ammonia[b]	4.2	8.2
2nd IPA	0	0.5
2nd ammonia	3.2	2.1
3rd IPA	0	0.4
3rd ammonia	1.2	1.8
4th IPA	0	0.1
4th ammonia	0.2	1.2

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Addition experiments

- Addition of extracted lipid material increases MED value and the water soluble substances lower these values.

Effect of adding soil extract fractions (lipids and water-soluble compounds) to samples of: untreated Himatangi sand and Himatangi sand that has been Soxhlet-refluxed.

Untreated	MED	Soxhlet-extracted	MED
Initial soil	2.8	Initial soil	0.2
Plus lipids only	4.6	plus lipids only	1.6
Plus water-soluble only	1.4	plus water-soluble only	0.2

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Addition experiments

- The lipid extracted from a wettable soil (Manawatu fine sandy loam) are equally effective at increasing MED as the lipids removed from the Himatangi sand

Effect of adding lipid extract from repellent and wettable soil on repellency

	MED Values		
Soil	**Initial value**	**Plus lipid from repellent soil[a]**	**Plus lipid from wettable soil[b]**
Waitarere sand	1.5	2.5	3.4
Himatangi sand	2.7	3.3	3.6
Foxton black sand	1.2	2.2	2.9
Castlecliff sand	2.1	3.0	3.0
Manawatu fine sandy loam	0	1.0	1.0

Addition experiments

- Ditto for the water soluble material

Effect of adding water-soluble extract from repellent and wettable soil on repellency.

	MED Values		
Soil	**Initial value**	**Plus water-soluble fraction from repellent soil[a]**	**Plus water-soluble fraction from wettable soil[b]**
Waitarere sand	1.5	1.0	1.0
Himatangi sand	2.7	1.5	1.0

3.3.7 Conclusions

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What does it all mean?

No obvious, single cause of repellency formation or expression emerges from consideration of the results presented above.

The lack of correlation between the MED value of the soils and their total carbon content, the quantity of lipid or of any lipid fraction extracted suggests that the severity of repellency can not be accounted for by the amount of lipid or of any lipid fraction in the 'bulk' soil.

Peculiarly, repellency of a soil sample can be made to fluctuate, in a serial manner, over a wide range of MED values depending on the sequence of solvents it is extracted in.

In terms of generating repellency, there is nothing unique about the compounds extracted from hydrophobic soils i.e. lipid compounds extracted from repellent soils seem no more efficient at imparting hydrophobicity than similar compounds removed from wettable soils.

A subtle mechanism is required to explain repellency expression in these soils.

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What does it all mean?

- Repellency seems to be a phenomenon best explained by reference to the nature of the surface that water encounters when attempting to infiltrate.
- More specifically, repellency is determined by the properties of the outer surface of the organic coating.
- Amphipathic compounds are key constituents of this outer layer. Given that differences in the MED values of these coastal sands can not be accounted for by concomitant variations in the quantity of bulk humus material, four possible mechanisms for repellency development and expression are proposed.

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Mechanisms for repellency expression

- Amphipathic compounds may change orientation. In the wettable context, these compounds are likely to have their polar end pointing outwards. If, for some reason, such as dehydration, there is re-configuration or re-orientation, then these substances may well present a water repellent end at the surface.
- Repellency may vary according to the ionisation status of carboxylic groups in amphipathic compounds. If protonated, this functional group will be hydrophobic in character: upon ionisation, the resultant charged carboxylate group will be mostly hydrophilic. The ionisation form of the carboxylic groups will be dependent on moisture content: in moist conditions, the carboxylate anion will be more common.
- The third mechanism relates to the extent to which the hydrophobic compounds are screened or covered. When the soil is wettable, the hydrophobic material is effectively screened, especially if the surface is well hydrated. Repellency may develop when the hydrophobic compounds are more exposed. For instance, this may be due to the contraction of carboxylate and other polar groups associated with dehydration described in mechanisms one and two above.
- Extraction and/or addition of compounds, be they water-soluble or lipid, may change repellency. The mechanisms proposed here are likely to interact. Indeed, the first three mechanisms might be thought of as, stages in, or parts of, a larger process.

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Conclusions

- Organic compounds were extracted from a range of coastal sandy soils using a number of extraction procedures and solvent mixtures.
- The extracted compounds were partitioned into operationally defined lipid and water-soluble fractions, and the constituent compounds identified.
- In the neutral lipid fraction, there are mostly alkane hydrocarbons and triglycerides; the acidic lipids are comprised of mainly long-chain fatty acids. The water-soluble fraction exhibits amphipathic behaviour, and plays an important role in repellency expression. This fraction bears some similarities with the hymetamelonic fraction of the humic acid pool.
- There is no clear relationship between repellency (MED value) and either total carbon content, that portion of the extract that is water-soluble, total extracted lipid or any lipid fraction.
- The repellency of soil samples can be modified *in vitro* by addition of soil lipid extract or water-soluble extract. This is so, regardless of whether the lipid and water-soluble extracts have been extracted from repellent or non-repellent soil. Water repellency is a surface phenomenon.
- Four mechanisms for repellency expression both in laboratory studies and in the field are proposed for further consideration.

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3.3 Soil hydrophobicity – Its significance to pastoral farming – The Hawke's Bay experience – *M Slay and M Deurer*

3.3.1 Background

Maraetotara is an elevated area (>620m) south-east of Hastings/Havelock North with high rainfall (>1600mm). Despite frequent showers of rain, pastures are subject to drying out in summer. For many years farmers in the area have observed and been concerned at the increase in a pasture condition in their permanent pastures. They describe it as 'Dry Patch Syndrome' (DPS) and it is clearly a widespread problem throughout the North Island.

As soil dries out through late spring, summer and into autumn, DPS manifests itself as irregular/occasionally circular areas of dried out pasture with exceptionally dry top soil. These areas can cover >60% of individual paddocks. Pasture production losses are estimated at 30%-40% per annum. Moreover, pasture is slow to respond to autumn rains and winter production is inhibited.

Figure 3.3.1.Symptoms of DPS in pasture at Ashley Clinton, Hawke's Bay (March 2007).

The major concern is that DPS is occurring in normally 'safe summer country' and the condition is becoming more widespread. The cause has been elusive and the phenomenon has been credited mainly to pasture insects, soil fertility or simply dismissed as 'bony country'.

In 2005, pasture mealybug (*Balanococcus poae*) was found to be causing pasture losses in the South Island. Pastures in the North Island were being investigated for the pest's presence. Mealybug was identified at Maraetotara. A Meat and Wool New Zealand project conducted a rigorous examination of the likelihood of this pest being allied to DPS. The project concluded that mealybug populations, though associated with DPS, were not commensurate with the exceptional pasture damage occurring.

However, mealybug provided a remarkable new learning curve. Is it possible the wax-like substance mealybug produce to avoid dehydration could inhibit water movement through soil? (Slay and MacGillivray 2007)

More rigorous examination of DPS patches revealed soil water repellency (SWR). A literature search showed SWR is allied to a condition known as 'Localised Dry Spot' (LDS), a major concern in the turf industry (especially golf courses). LDS is caused in part by a condition known as 'Soil Hydrophobicity'.

In permanent pasture, the key cause of soil hydrophobicity is the presence of low quality carbon caused in part by poor soil microbial activity and slow decomposition of OM especially hard to decompose vegetation (i.e. brown top)

3.3.2 Soil hydrophobicity project

In 2006-2007 eight DPS sites were analysed and compared with the adjacent 'green' pasture.

A range of soil tests were conducted by HortResearch (former name, now Plant & Food Research) in summer and winter to quantify: Whether the soil was hydrophobic or not and to determine the persistence of the hydrophobic soil (Water Droplet Test).The maximum 'Degree of Soil Hydrophobicity' of the soil (the contact angle of the water droplets with the soil surface were measured (MED Test), the higher the contact angle the more hydrophobic the soil surface).

The Critical Water Content was measured. Each site has a characteristic water content (%soil moisture) below which soil becomes hydrophobic and is key factor affecting pasture response to rain (Deurer *et al.* 2008).

Main results

- All sites were hydrophobic in summer and hydrophilic at end of winter.
- Dry patches were more hydrophobic that adjacent green areas.
- Soil was more hydrophobic in the top 3cm but the entire rooting zone was hydrophobic (to 7cm deep). 75% of all sites had hydrophobicity levels with contact angle above 97º, which are discussed as a threshold that limits pasture growth.
- Soil hydrophobicity decreased through winter but was still so high after winter that it could limit pasture growth.
- The **Critical Water Content** for one 'dry patch' and adjacent 'green' area was 35% and 22% soil moisture respectively. This means dry patches will repel moisture earlier in spring or attract moisture later in autumn following rain.
- Full testing strategy and results are available by accessing Final Report for FITT Project 04FT163 from Meat and Wool New Zealand.

3.3.3 Soil hydrophobicity – Significance to pastoral farming

The important issue is that a large number of soil types have the 'hydrophobic ingredients' (Doerr *et al.* 2006a) to cause soil hydrophobicity but they don't 'trigger' until the soil reaches certain dryness – ***The Critical Water Content (CWC)*** (Figure 3.3.2).

As pastures dry out in spring we observe changes in pasture colour, initially in patches fringed with green grass. With time the dry patches increase in size. Often, green areas remain quite green well into a drought.

What is happening below the soil? As soil dries out the amphiphilic molecules literally re-orientate themselves to the decreasing presence of soil water. Once the CWC is achieved the molecules' polar ends are well orientated (have turned 180º) to the moisture held tightly to the soil particle and their non-polar ends face outward, repelling water. In Australia this was known by early watershed workers as the **'Tin roof effect'** and describes exactly what is happening.

As drought intensifies and soil moisture falls further, the effect is intensified. Showers of rain in summer are repelled causing 'run off' and soil water storage is compromised. In dry patches, pasture plants can be killed and replaced by hardier less productive species.

Once autumn rains commence the rewetting process begins, but water will not 'freely' pass through the soil until the CWC has been reached (in this case 35% soil moisture). The time taken will depend on the frequency of rain and how dry the soil is.

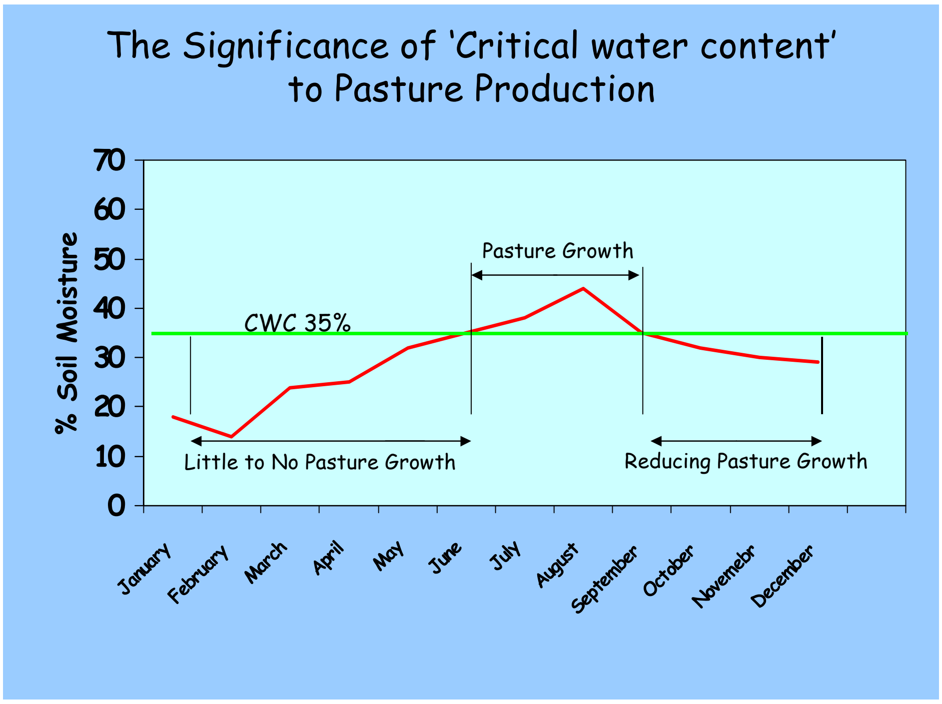


Figure 3.3.2. Relationship between soil moisture content and the CWC (35% at this site) in a hydrophobic dry patch at Maraetotara (2007) showing how it limits pasture production through the year.

The consequences of this phenomenon to pastoral farmers, farming predominantly permanent grasslands on lighter soils, are enormous. The hydrophobicity phenomenon describes exactly what Maraetotara farmers have observed. Similar conditions are observed elsewhere in Hawke's Bay and the North Island but not fully quantified. It is a widespread occurrence. It impacts strongly on soil water storage, efficient fertiliser use, pasture persistence and production.

Importantly, soil hydrophobicity is 'an additive' to drought, amplifying the situation. This condition will not go away. It has been grossly underestimated in pasture soil management. There is a need for ongoing research and for farmers to develop awareness of possible management strategies to reverse its impact on their business and the environment.

Irony…Soil hydrophobicity is a transient phenomenon and tends to mask its importance to the sustainability of pastoral farming.

'Once it is all green again we forget it –'until next time'.

3.3.4 Estimating the economic value of lost pasture on hydrophobic soils

This estimate is based on farmers' local knowledge and awareness of significant pasture losses from now identified soil hydrophobicity, particularly in autumn and winter. Other important factors they observe and report are delayed recovery of pasture in autumn reducing the opportunity for winter growth and the changes in pasture composition to less productive grasses.

In late summer the symptoms of soil hydrophobicity are not unlike that for grass grub. Thus visual estimates (%) of the area of a paddock affected are possible either by eye, photographs from adjacent hillsides or from the air (Kain 1975).

At Maraetotara, visually affected areas accounted for up to 60% of a paddock. Using this information and local knowledge it is possible to attempt an estimate of the loss in annual pasture production. *(Where loss in farm gross margin is proportional to the estimated pasture loss)* (Table 3.3.1*)*

Table 3.3.1 Estimated value of lost pasture production per ha with 60% visual symptoms of soil hydrophobicity.

Season	100% (No affect) Seasonal Kg DM/ha	60% of paddock affected = proportion of lost DM	% Loss per season to soil hydrophobicity	Kg DM/ha loss (annual) to soil hydrophobicity
Autumn	3000	1800	80	1440
Winter	2500	1500	70	1050
Spring	4000	2400	40	960
Summer	2500	1500	50	750
Totals	12000			4200 =35% loss in DM

With a farm gross margin of $1200/ha this represents an estimated loss in revenue of $420

3.3.5 Mitigation possibilities

In a recent review of soil hydrophobicity (Slay 2008), a range of mitigation options was considered. The key factor to mitigating soil hydrophobicity is undoubtedly managing soils to promote water infiltration…

Bioremediation – Use of wax reducing bacteria and lime. In Australia, Roper (Roper 2005) proposed a biological approach to managing SWR. She isolated a range of bacteria and actinomycetes that are able to utilise an extensive range of organic compounds as sole sources of carbon. They have the potential to decompose waxes responsible for SWR. For example, *Rhodococcus* spp. responds to alkanes (non polar) by producing bio-surfactant molecules that improve its ability to utilise hydrophobic compounds (Roper 2005).Sources of bacteria for trials were obtained from either non-wetting soils previously enriched with sewage sludge, animal fats, wool wax, faeces or composted animal manure. Roper's results concluded that inoculation with efficient 'wax degrading bacteria' had the potential to improve soil wettability.

Influence of lime on soil moisture. Roper, (2005) found the key limiting factor for improving soil microbial activity is moisture. For successful bioremediation there is a need in the first place to manage soils to promote water infiltration.

Clay spreading. Clay provides a physical interaction that modifies the hydrophobic nature of soils

Cultivation. Cultivation is the traditional method of 'thatch/turf' and weed destruction. As shown by Doerr (Doerr *et al.* 2006b), cultivated soils are virtually unaffected by SWR relative to permanently vegetated soils. Cultural practices used at Maraetotara reflect this. By using full cultivation in a pasture/crop rotation (in a highly SWR soil) new pastures initially performed satisfactorily (MacGillivray, Pers. comm.). However, dry patches re-appeared some three to five years later in areas that previously showed symptoms of SWR.

Minimum tillage. Given the nature of the light soil at Maraetotara and risks associated with wind and water erosion, direct drilling should be the preferred method of pasture establishment. However in theory this would only exacerbate SWR problems because:

- there is no mixing of the soil and redistribution of more hydrophobic top soil,
- in dry seasons the high incidence of poor water infiltration and dry spots would inhibit germination and/or cause 'false strikes' of seed and uneven pasture establishment,
- lime and fertiliser cannot be incorporated into the soil, and
- hard-to-control grass weeds known to cause SWR problems re-establish quickly so longer term pasture persistence is compromised.

Turf/soil aeration/grazing 'hoof and tooth'. There is a range of tractor mounted/towed mechanical 'aerators' being used to assist with the breakdown of surface thatch

Mulches. Mulches can provide rich sources of soil bacteria and microorganisms

Grazing management. Once new pastures are established efforts to minimise pasture reversion is paramount. Maintenance of soil nutrients, good grazing management and utilisation are key parameters to extend pasture life and improve the quality of organic matter. Ongoing commitment to improving soil biological status is critical.

Surfactants/wetting agents. Wetting agents may offer a temporary opportunity to improve soil water infiltration post drought that facilitates germination and more even infiltration of water and applied soil nutrients into the soil. The economic benefits of wetting agent use in agriculture require careful research on behalf of the user in terms of the degree of SWR on farms and economic benefit.

Humates. The involvement of humic acid and especially fulvic acid relative to SWR requires further clarification.

Earthworms. Key factors to encourage worms are organic material, calcium, soil moisture and temperature. Low worm populations are often associated with low calcium levels and a soil test of at least 7 is recommended (MAF test). Soils with the highest degree of hydrophobicity at Maraetotara had Ca levels of 3-4 (Stockdill 1984).

3.4 What observations have you made in your region? – Group discussion *chaired by A Mackay*

The group discussion focused on observations of soil hydrophobicity (SH) by the workshop participants. Does soil hydrophobicity exist? How extensive is it?

General around-room discussion on observations of SH (or something with similar symptoms); comments were recorded in an approximate chronological order. No other order is implied.

- SH probably has an impact on argillitic soils – often low pH, drought-prone sites, but perhaps also in higher rainfall areas; observed on convex slopes; participant commenting on observations on sheep and beef farms – unsure of situation on dairy farms.

- Has been observed in Taranaki on hard sandstones with low ground covers; obvious occurrence on allophanic soils; SH unknown on dairy farms, but not specifically looked for.

- SH is commonly observed in pastures in Waikato; could occur on drying gley soils; not well known by farmers, suggesting need for raising awareness of phenomenon.

- SH has been observed on moderate to steep slopes – not just on gently sloping land.

- Observed on Brown soils, ash, north and south slopes (with differences in extent and rate of expression of SH symptoms).

- Under variable fertility in coastal Hawke's Bay, the extent of involvement of SH is uncertain.

- SH has been observed in summer dry/winter wet areas of Wairarapa.

- At AgResearch's Ballantrae Hill Country Research Station, there has been no effect of aspect on the presence and distribution of SH, based on a laboratory assessment of the soil; an assessment in situ was not conducted.

- Interactions between vegetation type/form and SH have not been identified, or defined well.

- In the South Island, SH exists and it is thought to be widespread.

- Soil texture and structural aggregation are important determinants of the presence and extent of SH.

- It is possible that SH may become apparent following land use change, e.g., forestry to dairy. SH-like symptoms have been observed in some instances.

- Perhaps consider the interactions between SH and irrigation scheduling/effluent disposal.

3.5 Hands-on demonstrations of the measurement and impact of soil hydrophobicity – *K Müller, M Deurer, C van den Dijssel, J Carter*

During the workshop there were three hands-on demonstrations.

3.5.1 Measurement of the persistence and degree of soil hydrophobicity

Figure 3.5.1. John Carter (Production Footprints team, Plant & Food Research) explains the Water Drop Penetration Time Test as a measure of the persistence and the Molarity of Ethanol Droplet Test as a measure of the degree of soil hydrophobicity to workshop participants. Currently, John Carter works as an AGMARDT funded postdoctoral fellow on the economic and environmental impact of soil hydrophobicity.

A simple measurement that anyone can do to assess the persistence of soil hydrophobicity in the field is the Water Drop Penetration Times Test. Droplets of water are placed on a soil surface and the time it takes for the drop to infiltrate is recorded. The Molarity of Ethanol Droplet Test assesses the degree of soil hydrophobicity. John Carter demonstrated the tests for different hydrophobic soils under pasture that he had recently collected in a survey on the occurrence of soil hydrophobicity in soils of the North Island (Fig. 3.5.1). These were an ‘Organic’ soil from Taranaki, a ‘Recent’ soil from Hawke’s Bay, and a ‘Brown’ soil from an area close to Wellington. John provided a handout for each of the soils with a photo and some key site and soil characteristics (see Appendix 3.1). More details on the measurements of soil hydrophobicity are given in Section 3.1.3.

3.5.2 Reduction of water infiltration rate by soil hydrophobicity

The reduction of the water infiltration rate into soils is one of the major impacts of soil hydrophobicity (for more details see Section 3.1.7). It can be measured by comparing the infiltration rates of water and ethanol. Due to the low surface tension of ethanol solution, soil hydrophobicity has no influence on the infiltration rate of ethanol.

Figure 3.5.2. Karin Müller (Production Footprints team, Plant and Food Research) explains the measurement of water and ethanol infiltration into a hydrophobic soil that was taken from AgResearch's Hill Country Research Farm, Whatawhata, near Hamilton.

3.5.3 Generation of run-off and overland flow by soil hydrophobicity

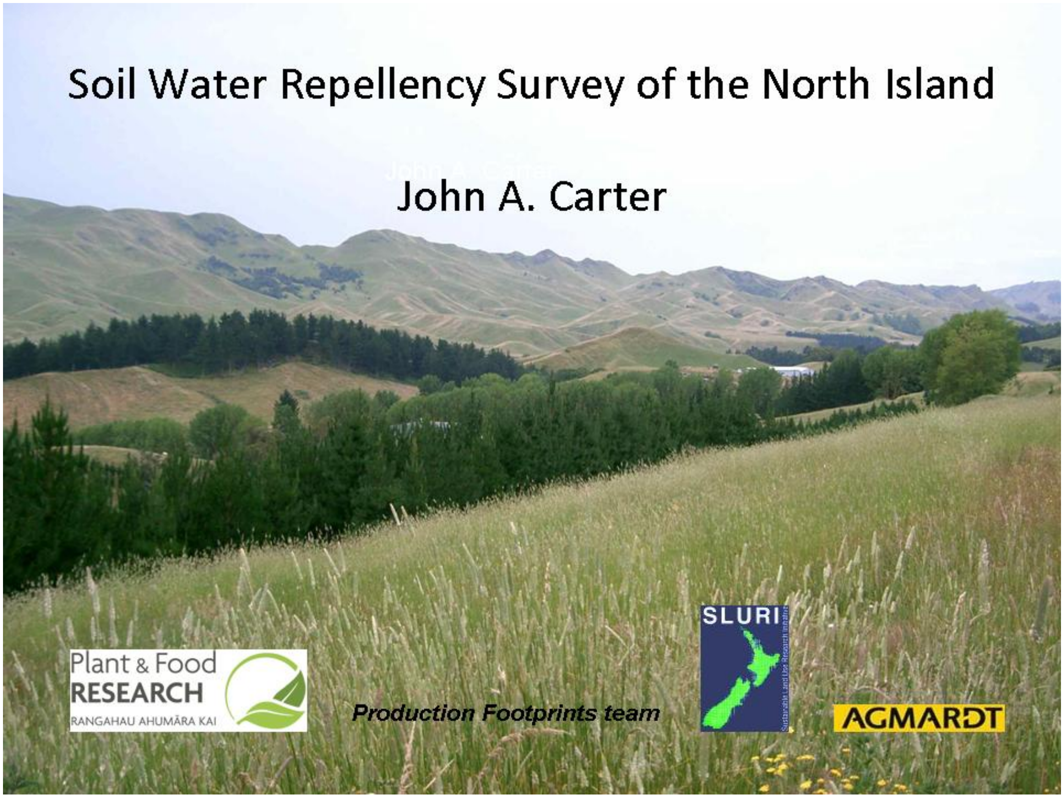
Soil hydrophobicity decreases the infiltration rate of water into soils and, especially on hillslopes, subsequently generates run-off and overland flow (for more details see Section 3.1.8). For the workshop, we developed a portable apparatus to measure the influence of soil hydrophobicity to enhance overland flow (Fig. 3.5.3). With the apparatus we introduce overland flow across the upper boundary of a soil slab. Water can then either flow through the soil (no run-off) or over the soil surface (runoff). The water that flows through the soil is collected separately from the water that flows over the soil surface and leaves the slab across its lower boundary. Different slope angles and overland flow rates at the upper boundary of the soil slab can be adjusted.

We demonstrated the occurrence of runoff for two sites with hydrophobic soils.

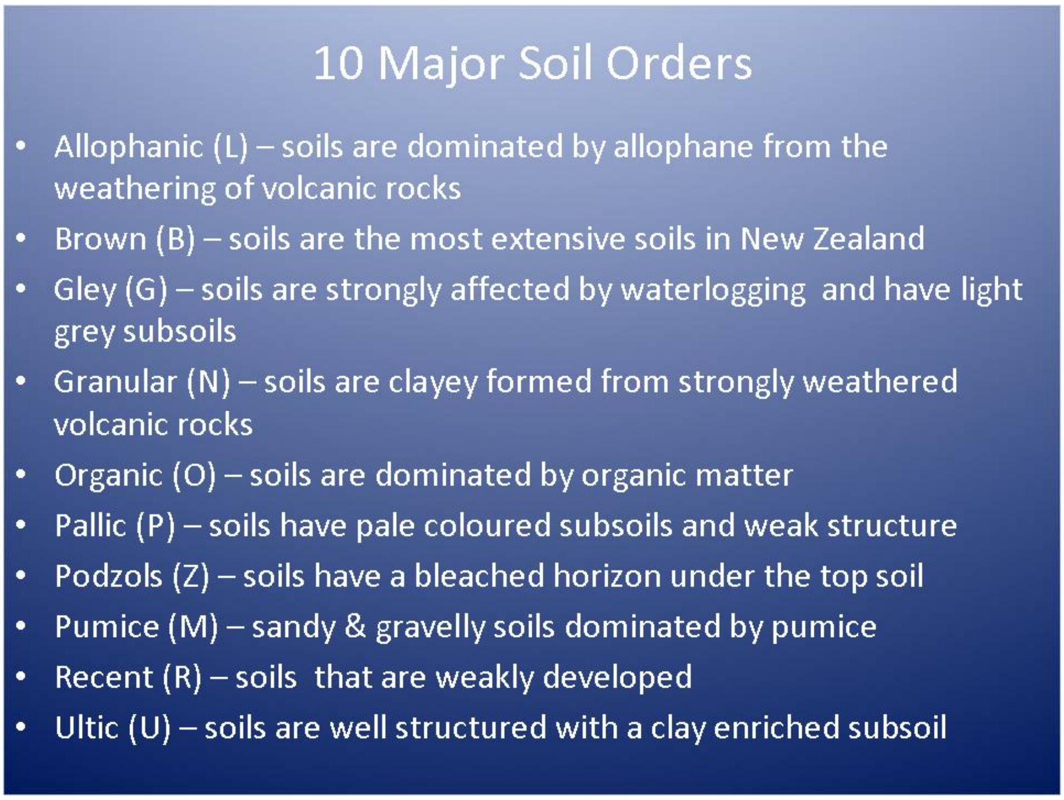
Site 1 was a hydrophobic soil under sheep/beef pastoral land use from Maraetotara in Hawke's Bay, and site 2 was a hydrophobic soil under sheep/beef pastoral land use from AgResearch's Hill Country Research Farm at Whatawhata near Hamilton. Run-off quickly occurred at site 1, but also quickly decreased as soil hydrophobicity was not very persistent. At site 2, run-off also quickly occurred but hardly decreased over time as soil hydrophobicity was very persistent.

Figure 3.5.3. Markus Deurer (Production Footprints team, Plant and Food Research) explains the functions of the run-off apparatus. The apparatus can be used to measure the influence of soil hydrophobicity on run-off and overland flow.

3.6 Soil water repellency survey of the North Island – *J Carter,* C van den Dijssel, K Mason, K Müller, M Deurer



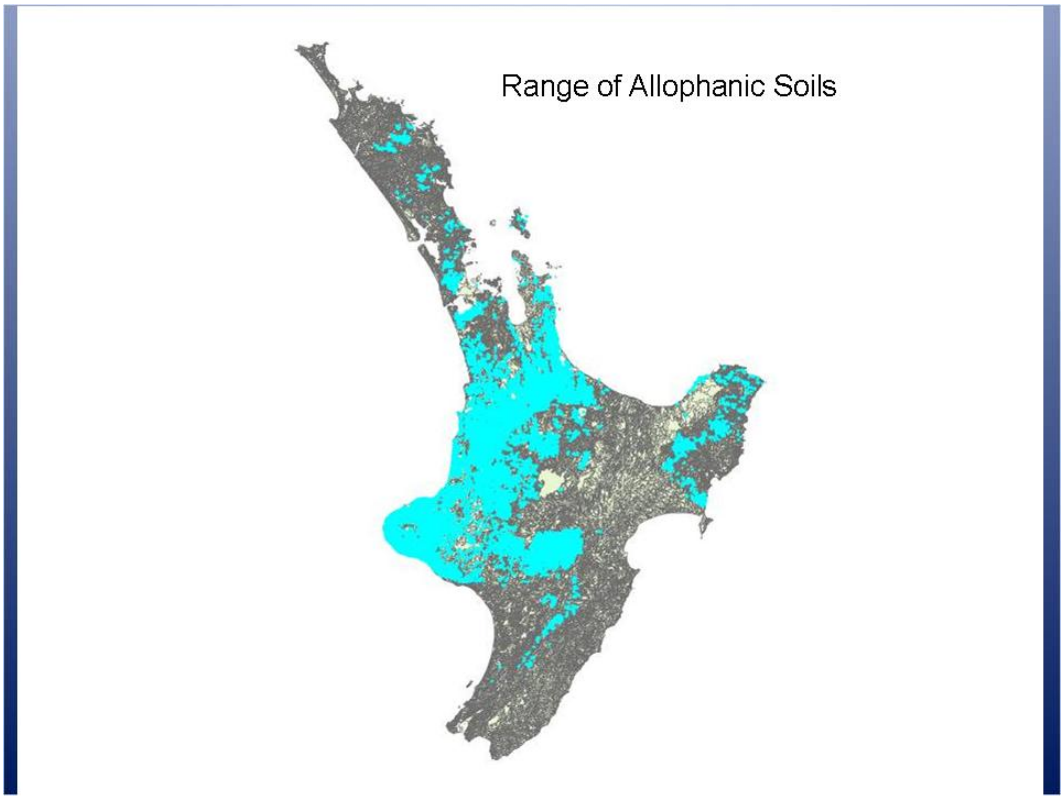
3.6.1 Selection criteria for sites for the survey

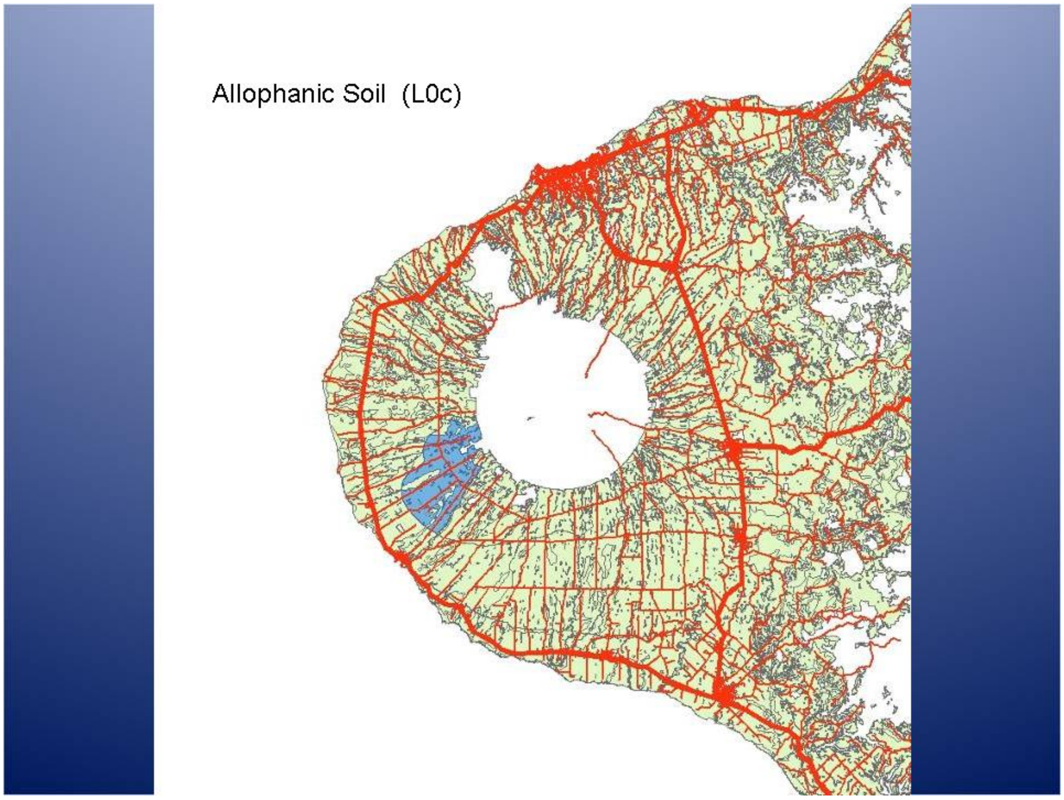


Annual Water Deficit (AWD)
(measure of climate effect on soil moisture)
0 = 0 mm
1 = 0-50 mm
2 = 50-396 mm

Profile Readily Available Water (PRAW)
A = 150-250 mm
B = 100-149 mm
C = 75-99 mm
D = 50-74 mm

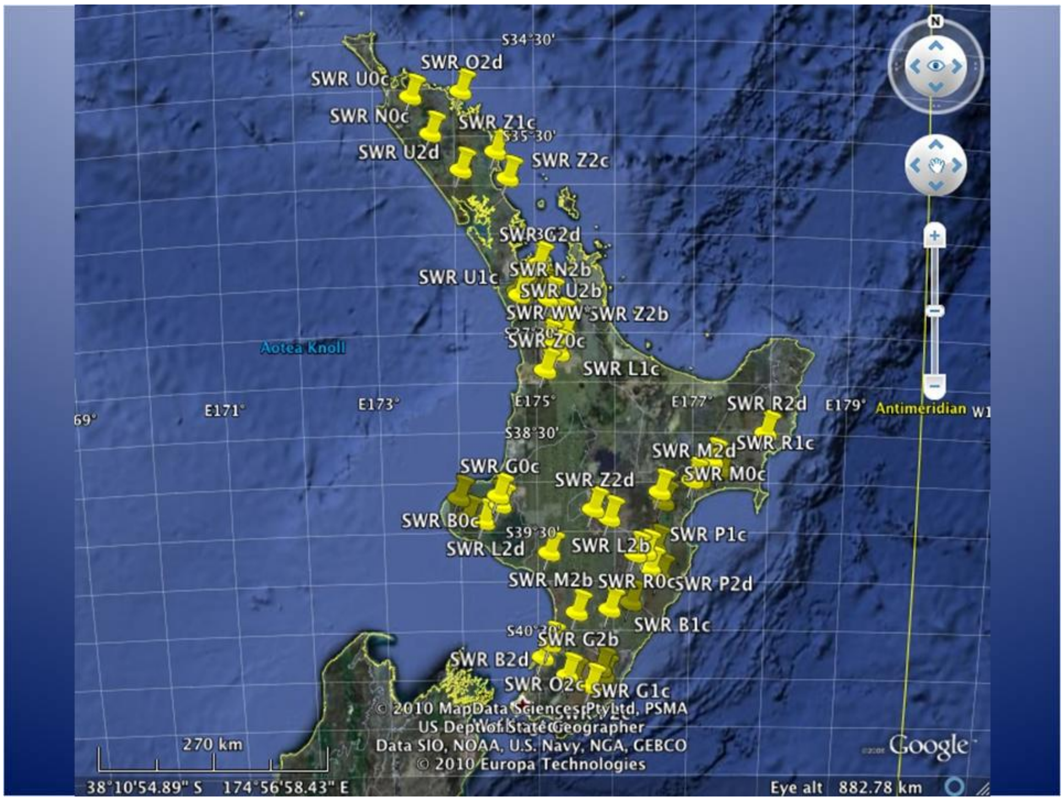
3.6.2 The example of Allophanic soils with no water deficit and 75-99 mm plant available water (L0c)



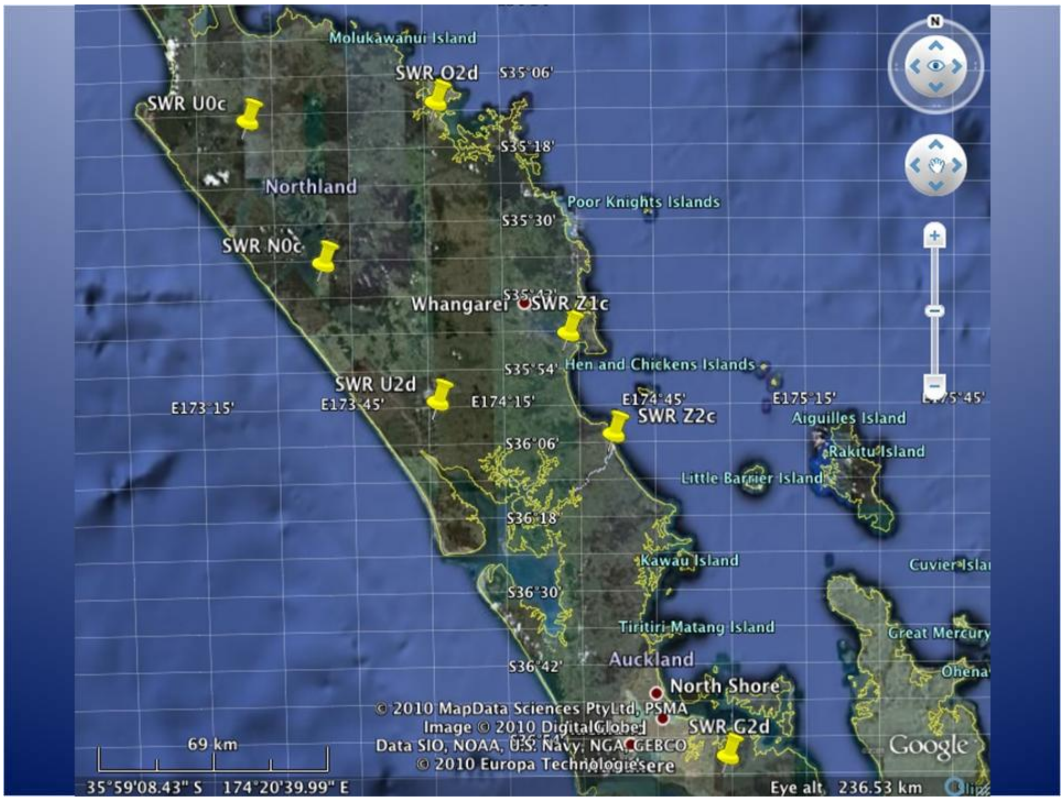

Allophanic Soil (L0c)


Dairy Farm, Wiremu Road, Taranaki
•Allophanic Soil,
•Location: S39° 20.470, E173°54.319
•0 Annual Water Deficit ,
•75-99mm Profile Available Water,
•Flat lying but surrounded by hummocky lahar debris

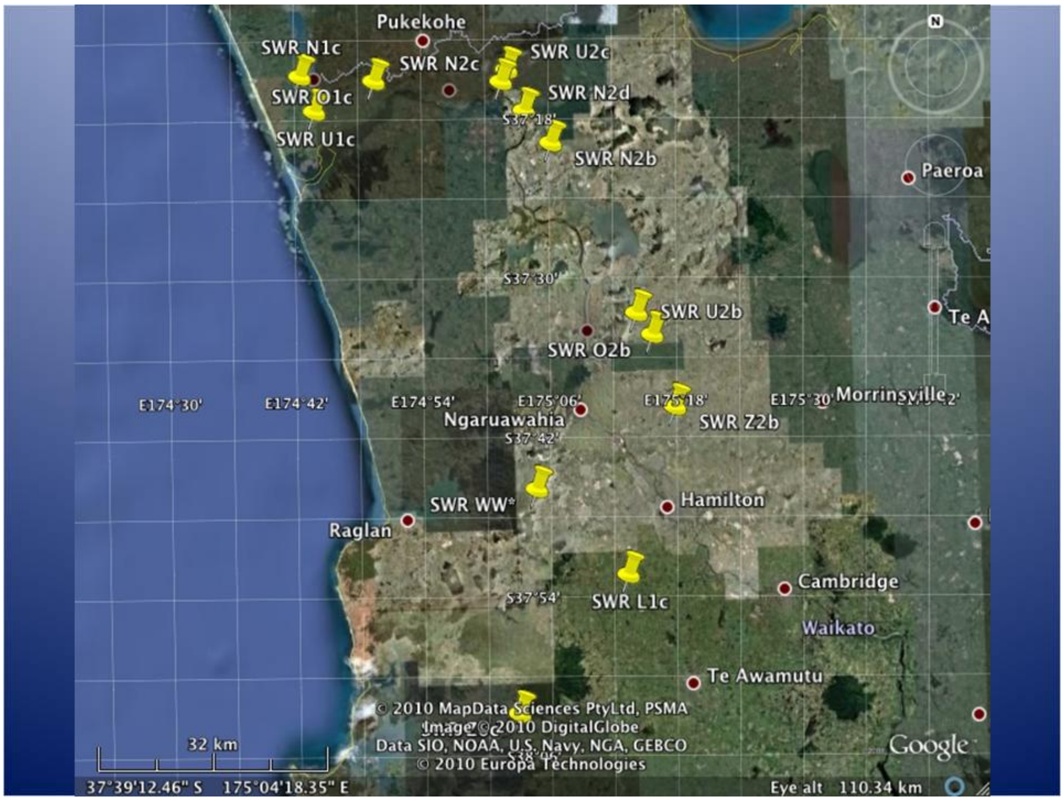
3.6.3 Sites across the North Island



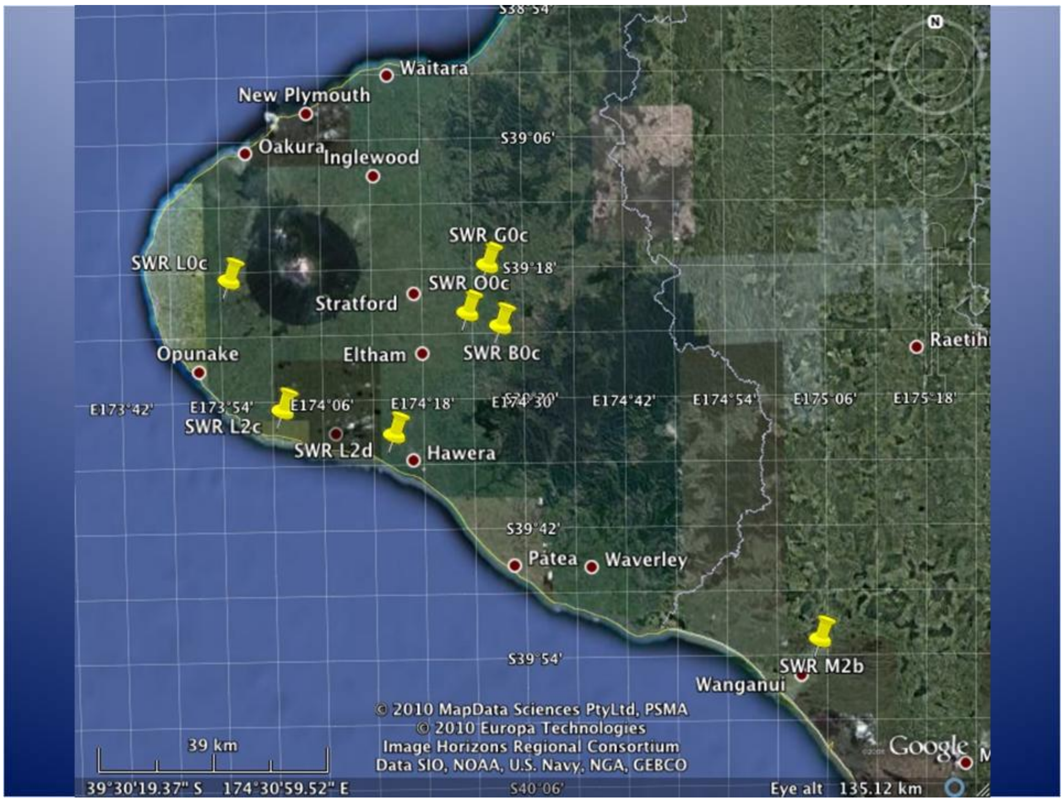
3.6.4 Sites in Northland



3.6.5 Sites in the Waikato



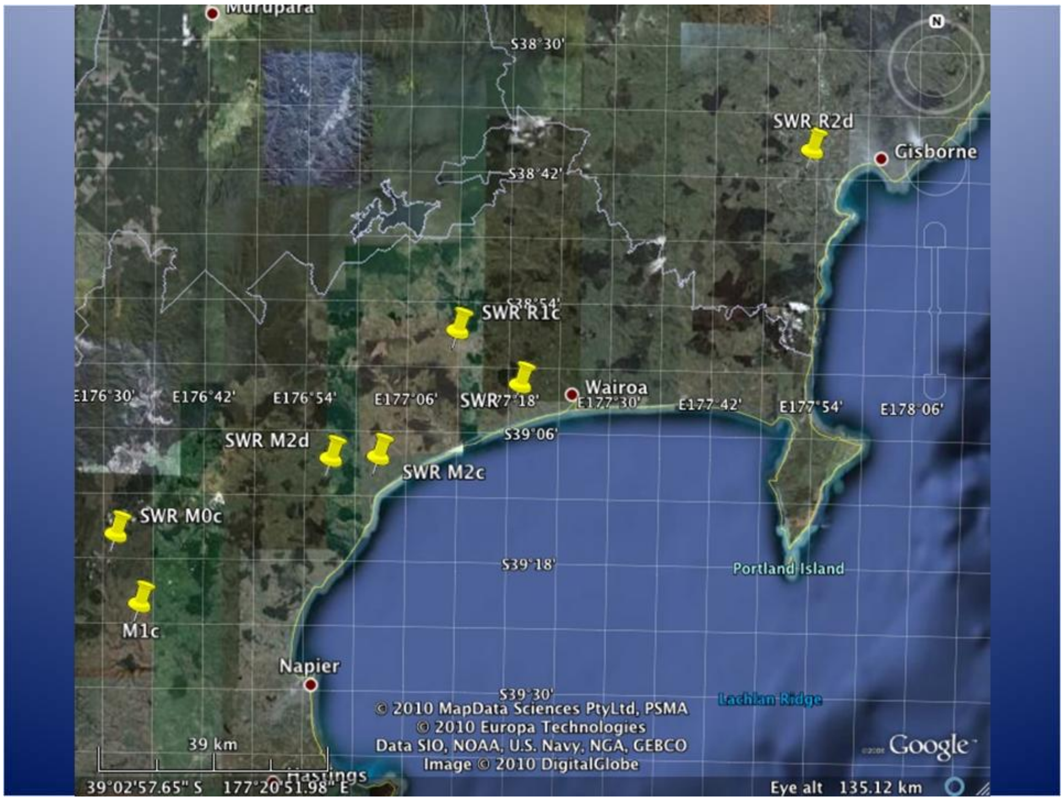
3.6.6 Sites in Taranaki




Dairy Farm, Eltham, Taranaki
•Organic Soil (O0c)
•Location: S39° 23.815, E174° 22.699
•0mm Annual Water Deficit ,
•75-99mm Profile Available Water
•Degree of hydrophobicity (Contact Angle) 103.173°
•Hydrophobic at time of sampling (Field moist sample WDPT) 180 minutes
•Potential hydrophobicity (Dry Sample WDPT) 210 minutes
Organic – O0c


Cattle & Sheep Farm, Stratford, Taranaki
•Brown Soil (B0c)
•Location: S39° 20.065, E174° 26.581
•0mm Annual Water Deficit ,
•75-99mm Profile Available Water
•Slope 14° W
•Degree of hydrophobicity (Contact Angle 101.419
•Hydrophobic at time of sampling (Field moist sample WDPT) 7 minutes
•Potential hydrophobicity (Dry sample WDPT) 135 minutes
Brown – B0c

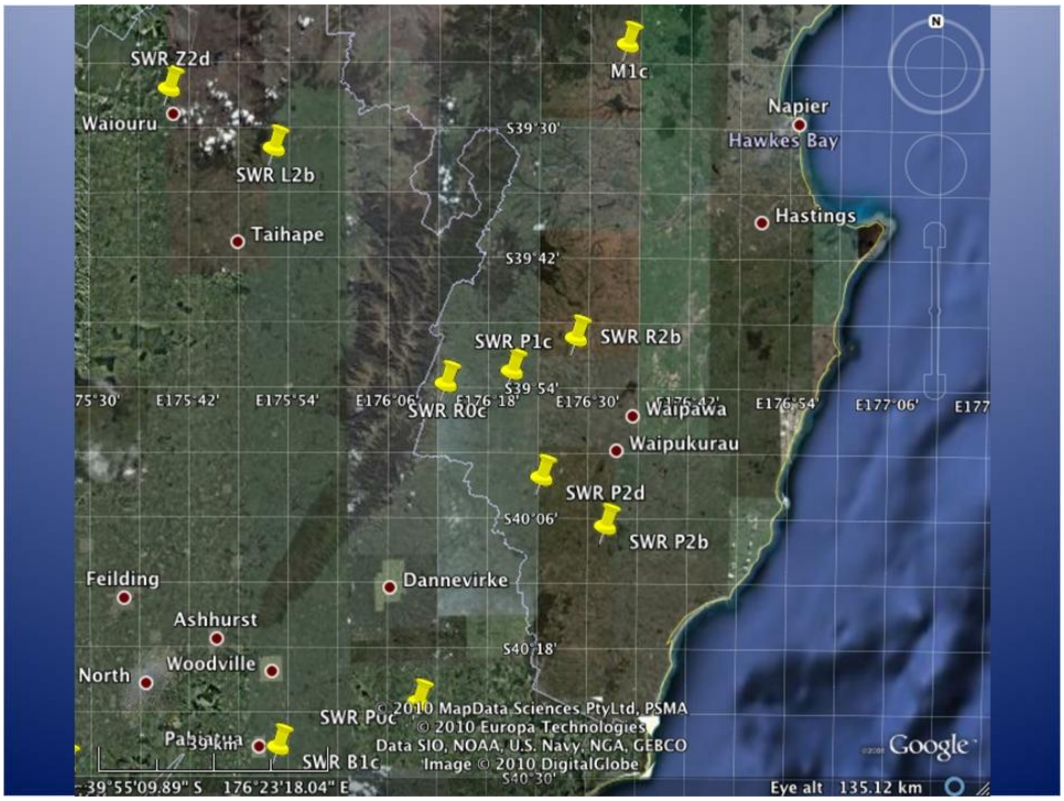
3.6.7 Sites in the Hawke's Bay



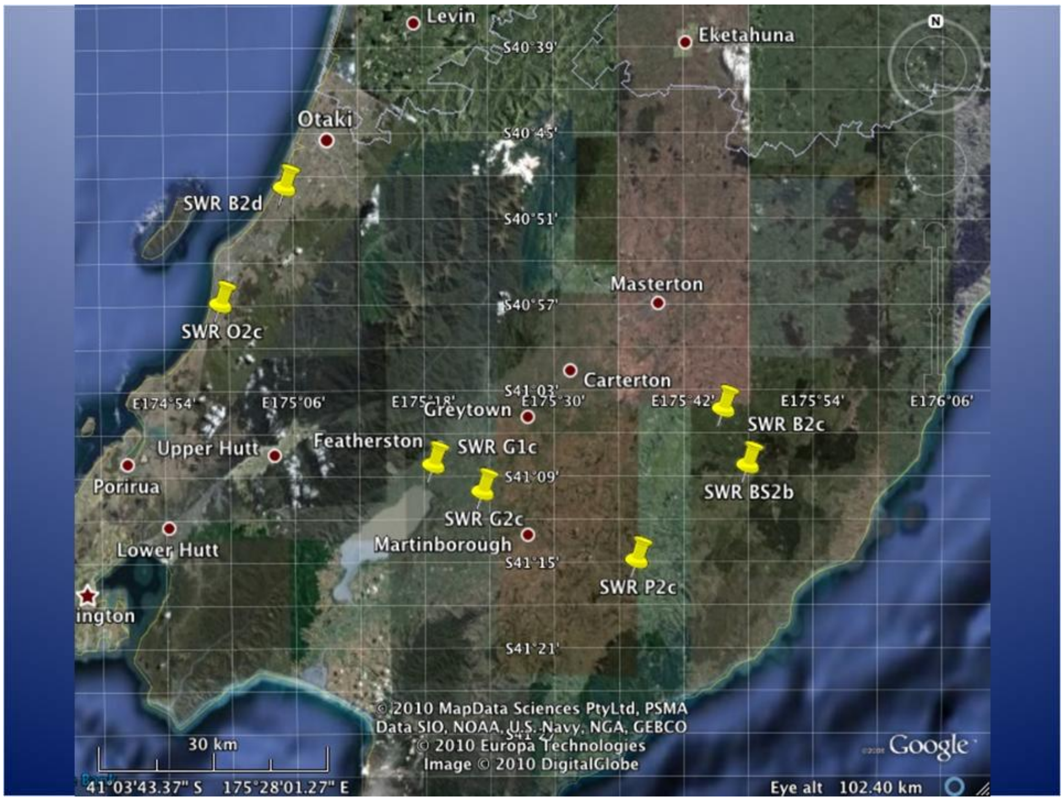

Sheep and Cattle Farm, Putorino, Hawkes Bay
•Pumice Soil,
•Location: S39° 1682, E177° 0339
•50-396mm Annual Water Deficit ,
•75-99mm Profile Available Water
•Slope 20°, 150° South
Podzol – M2c


Sheep Farm, Ashley Clinton, Hawkes Bay
•Recent Soil (R0c)
•Location: S39° 55.396, E176° 12.218
•0mm Annual Water Deficit ,
•50-74mm Profile Available Water
•Slope 20° SE
•Degree of hydrophobicity (Contact Angle) 101.878°
•Hydrophobic at time of sampling (Field moist sample WDPT) 120 minutes
•Potential hydrophobicity (Dry sample WDPT) 195 minutes
Recent – R0c
R0c

3.6.8 Sites in the Manawatu and Hawke's Bay



3.6.9 Sites in the Wairarapa and Wellington

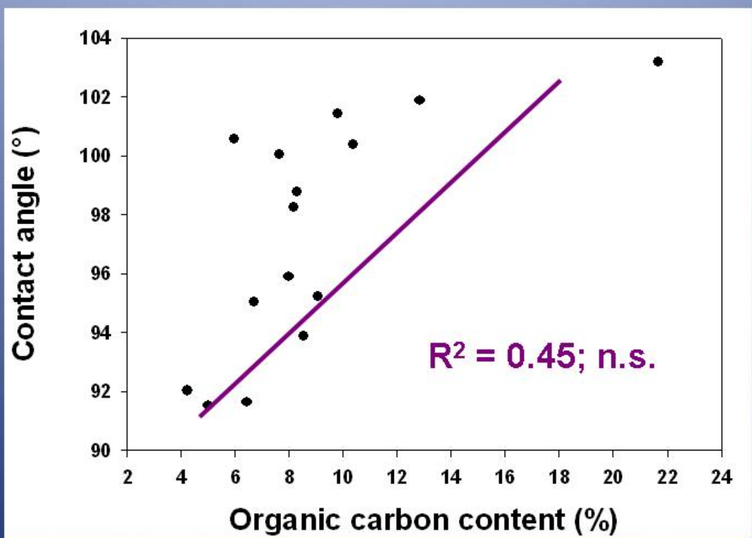



Mixed Farm, QEII Park, Wellington
•Organic Soil (O2c)
•Location: S40° 9698, E174° 978
•50-396mm Annual Water Deficit
•75-99mm Profile Available Water
•Degree of hydrophobicity
(Contact Angle 100.026
•Hydrophobic at time of sampling
(Field fresh sample WDPT) 50
minutes
•Potential hydrophobicity
(Dry sample WDPT) 195 minutes
Organic – O2c

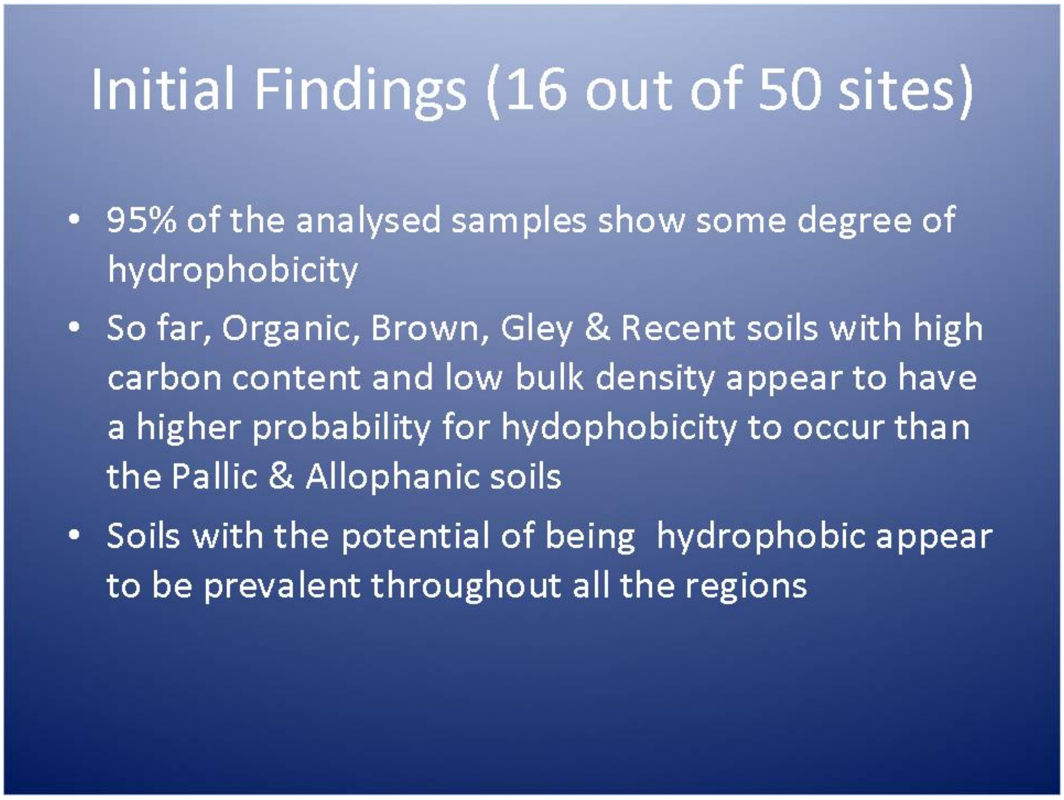

Farmlet, Pekapeka, Wellington
•Brown Soil (B2d)
•Location: S40° 9698, E174° 978
•50-396mm Annual Water Deficit ,
•50-74mm Profile Available Water
•Slope 12° SSW
•Hydrophobic
•Degree of hydrophobicity
(Contact Angle 100.547
•Hydrophobic at time of sampling
(Field moist sample WDPT) 3
minutes
•Potential hydrophobicity
(Dry sample WDPT) 60 minutes
Brown – B2d

3.6.10 Preliminary results for the first 16 sites of the survey

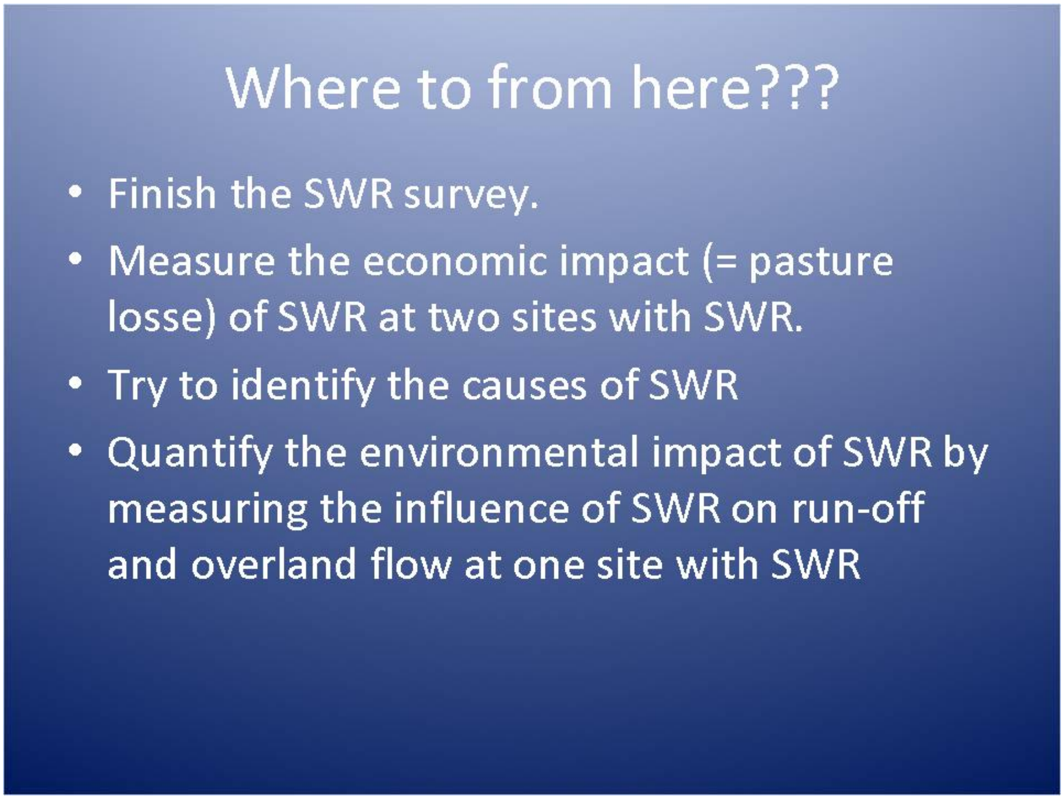
Region	Soil Order	Sample	Carbon %	Contact An	Bulk Density	pH	Actual (Min)	Potential (Min)
Taranaki	Organic	O0c	21.683	103.173	0.557	4.5	180	210
Wellington	Organic	O2c	7.648	100.026	1.026	4.4	50	195
Taranaki	Brown	B0c	9.805	101.419		4.9	7	135
Wellington	Brown	B2b	6.697	95.043	1.033	4.2	2	3
Wellington	Brown	B2c	4.998	91.505	1.183	4.9	2	1
Wellington	Brown	B2d	5.945	100.547	1.072	4.9	3	60
Hawkes Bay	Recent	R0c	12.833	101.878	0.666	4.5	120	195
Hawkes Bay	Recent	R2b	8.180	98.247	0.921	5.6	29	27.5
Manawatu	Pallic	P0c	8.288	98.780	0.822	5.0	8 seconds	70
Hawkes Bay	Pallic	P2d	4.575	<90	1.282	4.6	1	5 seconds
Taranaki	Allophanic	L0c	8.540	93.885	0.665	4.7	0	47.5
Taranaki	Allophanic	L2c	9.063	95.207		5.0	0	3
Taranaki	Allophanic	L2d	7.978	95.902	0.722	5.4	0	3
Taranaki	Gley	G0c	10.368	100.376	0.625	4.9	1 second	90
Manawatu	Gley	G2b	4.225	92.025	1.211	4.3	1 second	47.5
Wellington	Gley	G2c	6.432	91.637	1.096	4.8	5	24 seconds



Positive correlation between TOC and SWR.
But, TOC alone is not a reliable predictor of SWR.
Quality of organic matter and soil biology are equally important.



3.6.11 Next steps




Acknowledgements:
Thanks for funding and support from
AGMARDT
and
SLURI
Plant & Food
RESEARCH
RANGAHAU AHUMĀRA KAI
Production Footprints team
SLURI
AGMARDT

3.7 The occurrence of hydrophobic soils in golf course fairways and its management and control – *G Walker*

3.7.1 Background

This study has been driven by the challenges facing the four Waikato River golf courses (Hamilton, Lochiel, Ngaruawahia, and Cambridge), to improve fairway turf quality. Hydrophobic soil has been the central issue. The study spans six years of observation and intermittent work for these golf clubs.

The Aim of this study. To identify drought tolerant grasses to reduce water requirements in the future.

Conclusions. The grasses identified as drought tolerant are brown top and fescues**.** To establish these drought tolerant grasses, soil quality is paramount, meaning “living soil” with a natural balance of air, water, organic matter, humus and biota (micro-organisms).

Golf clubs generally throughout New Zealand are failing to understand that this matter along with many other challenges need to have a comprehensive mid- to long-term ‘plan’ so that the finances and skills required can be provided.

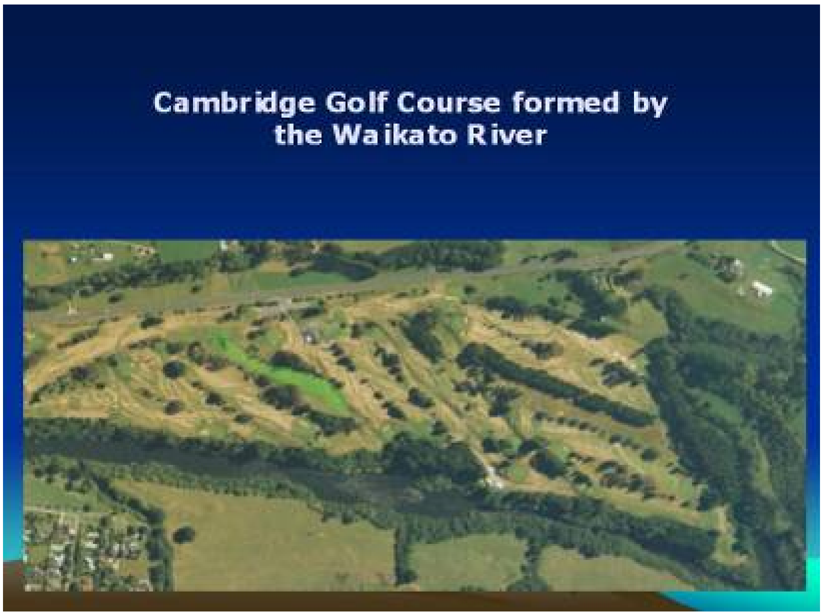


Figure 3.7.1. View of the Cambridge Golf Course.

All fairways have similar soils based on Taupo pumice carried down by the river.

There is evidence that the soils have a good nutritional balance.

This seminar will be very helpful to the process of educating these clubs

3.7.2 Soil degradation - Why golf clubs have allowed this to happen

- This is a major topic on its own.
- Very slow deterioration over at least the past 20 years and although there is little information, it would appear for up to 50 years.
- The low budgets that these clubs adhere to will be one reason.
- Poor management, ignorance and member politics have played a major part.
- In the writer's opinion, the sports turf industry has been encouraged over the past 40 years to use practices based on chemical solutions but are now slowly acknowledging the practices of earlier years.

Golf clubs generally are now starting to act and not before time.

- Golf is in a very competitive "sport and recreation market."
- Television coverage over the past 20 years has created a member expectation.
- General presentation including fairway condition needs to improve.
- Environmental considerations and sustainability messages are being acknowledged.
- Future water usage and costs are now becoming a priority.
- In the writer's opinion more effort is required.

3.7.3 Soil hydrophobicity and soil compaction – typical signatures of degraded soils of golf course fairways

Figure 3.7.2. Low water infiltration and storage in hydrophobic soil cores taken from fairways of the Hamilton Golf Club after a heavy rain event (Easter 2006).

The cores sampled after a major rain event (100 mm of rain over the four days of Easter, 2006; Fig. 3.7.2) at the Hamilton Golf Club are excellent examples of a degraded hydrophobic soil. The thatch layer is wet and acts like a sponge while the rest of the hydrophobic topsoil remains very dry.

The reasons for this hydrophobic condition are many but compaction is the starting point.

- Compaction from machinery—frequent mowing

Compaction starts the process that changes the balance and structure of soil.

- Reduced air content
- Anaerobic conditions – oxygen content is low, carbon dioxide level is high
- Lowers infiltration rate
- Root penetration becomes very difficult
- Reduced soil drainage
- Changes in micro-organism activity

But golf practices just for good measure have aggravated the situation by;

- No worms – worm castes were declared a nuisance so worms have been reduced or even eradicated.
- Clovers, daisies, flat weeds, paspalum and summer grasses, again for various reasons have been hit annually with chemicals to eliminate.
- Because the soils finally lost quality, the strong almost natural grasses, fescues and brown top have disappeared.

Poa annua, a common meadow grass worldwide, takes over, and finally will seal off the surface.

- Seeds prolifically
- Grows in compacted and hydrophobic soils.
- Grows too much thatch and then grows in the thatch, which seals off the surface.
- Thatch harbours disease.
- Needs too much water
- And then dies when you need it most

Figure 3.7.3. Comparison of poa annua and fescue dominated turfs. These photos (above), both of the identical location were taken at the Cambridge Golf Club three months into the drought of 2008 and the situation was the same at end (four months).

Main features

- Fescues in good soils and poa annua in poor soil (confirmed by soil tests).
- Fescues retained colour and good plant density/length right throughout the 2008 drought.

3.7.4 Recovery and management of degraded soils

The recovery process is very simple;

1. Reduce/reverse compaction by starting with aeration machines
2. Encourage worms
3. Microbial life will follow.
4. Various quality grasses start to re-appear.

Figure 3.7.4. Tumble corer (**left**) for aeration and decompaction for soils of golf course fairways (**right**).

For fairways, the tumble corer is ideal for aeration and decompaction – simple, effective and at very low cost (Fig. 3.7.4). The mechanical tools for sports turf have in the main been around for many years. Mechanical tools such as; corers, slicers, scarifiers, spikers, Vibramoles, deep ripper (if desperate). Sports turf generally recovers and repairs very quickly. Using a drag mat to disperse soil and grass debris, the ground is back in play on the day and healed usually within three to five days.

Figure 3.7.5. Dethatcher or scarifier (left) and Vibramole (right).

Other machines that help to reverse the soil degradation of golf courses are the dethatcher and the Vibramole (Fig. 3.7.5). The dethatcher

- is used to remove the poa annua thatch which often is a dense shield from growing in itself.
- This thinning process creates a good seed bed.

The Vibramole

- slices to a depth of 100ml to 150ml (6 inches) in good conditions,
- creates very little disturbance,
- aerates and decompacts,
- is good for winter drainage preparation.

Most golf course trainees cut their teeth on golf greens and the rules that apply to greens are the same for fairways.

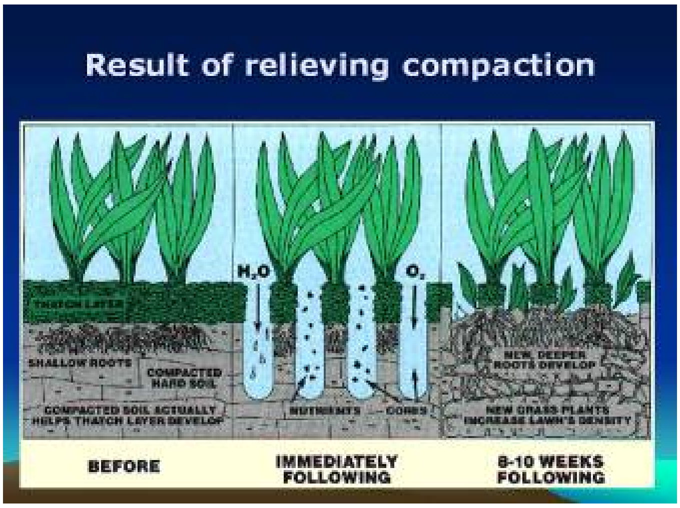


Figure 3.7.6. Schematic view of benefits of soil coring for turf greens. Coring is the golfer's nightmare, but it is vital for the soil quality that this work is carried out.

Soil structure. The aim is to achieve 'living soil' which further decompacts the soil and regains porosity. This can be enhanced by coring (Fig. 3.7.6). A healthy soil structure is, for example, necessary to sustain a high level of microbial life in soil (Fig. 3.7.7). Robust microbial life in the soil creates the humus that facilitates water infiltration and storage. This provides stable food sources and disease protection for turf, pore space for worms, water and root systems.

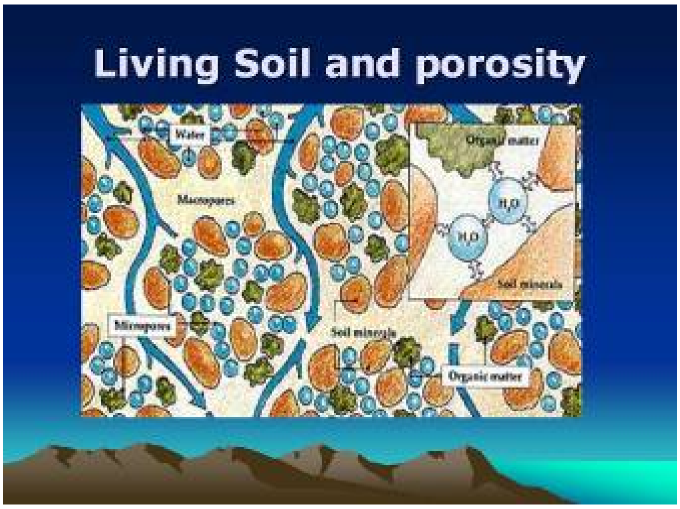


Figure 3.7.7. A healthy soil structure contains enough porosity to sustain a high microbial activity.

Another important component of soil biology is earthworms.

- To encourage worms – aeration and calcium
- Lime (provides calcium) in the first instance to encourage and assist worms.
- Calcium – most important mineral
- Most abundant mineral in animal/human body
- Most important mineral in the soil

Soil test should accompany the recovery management of degraded soils.

Soil Tests

- The information required for balancing minerals is available in the soil test
- pH, mineral, CEC, base saturation, organic matter
- Base saturation percentages and Cation Exchange Capacity are key indicators
- R J Hill Laboratories have produced a very good brochure on CEC and base saturation
- They include both in their basic soil tests.

Feeding the soil to speed up the process. Biological treatments are to balance minerals and encourage/feed microbial life in the soil. Aeration before biological treatments are applied is helpful. Biological treatments will work faster in decompacted soil. Biological treatments should include humic acids and trace minerals along with calcium and magnesium.

Compost is an answer, except "poor compost is worse than no compost at all!"

Many are now realizing the cultural practices of the past 100 to 300 years should not be ignored. Compost application led to very good results for the soil quality of a major horse stud in Cambridge, the outcome of many years of study and application. With the right mineral balance and biology, everything else will follow

The use of durable, and drought tolerant grasses is essential (Fig. 3.7.8).

- Strong grasses need quality/living soil to survive
- In time they will overpower weak grasses
- The best of the fine grasses are fescues and brown top for our four Waikato golf courses
- What grows above ground is only as good (or as bad) as below ground!

Figure 3.7.8. Comparison of a fescue and brown-top dominated versus a poa annua dominated freeway without irrigation in February 2010. Left: Martinborough Golf Course where freeways are dominated by fescue and brown top. Right: Cambridge Golf Course where freeways are dominated by poa annua.

The benefits of a soil with a high quality are:

- Stronger root structure
- Effective water infiltration
- Effective drainage at the surface
- Less water will be required because strong and fine grasses that are drought tolerant will get stronger and obviously require less water
- Weak grasses are over-powered eventually
- Consistent summer and winter condition
- Reduced disease
- Lower costs

This paper is about achieving soil quality and highlights the move to understanding soil health/quality and the vital part soil plays in the health of plants, animals and humans.

3.8 Where to go from here? – Group discussion *chaired by G Douglas*

The final group discussion focused on what kind of future activities are needed to address the problem of SH. The discussion could be divided in three parts.

3.8.1 Education/Awareness

- Sustainability needed for survival of industry and soil hydrophobicity threatens sustainability (economic and environmental)
- Distribute knowledge now through media, e.g. periodicals of farming community
- Key deliverables for education:
  - Financial impact of hydrophobicity (robust numbers needed)
  - Mitigation options need to be known

3.8.2 Research gaps

- How do we get the moisture back into the soil (mitigation strategies)?
- What are the key factors causing soil hydrophobicity in New Zealand? More research needed (scale impact estimates). What are the key factors for impacts of soil hydrophobicity?
- What is the merit/risk of various treatments? (e.g. direct drilling, liming, bioremediation)

3.8.3 Top 10 recommendations for future activities around soil hydrophobicity

1. What are the key factors causing soil hydrophobicity in New Zealand – more research is needed
2. Test various mitigation treatments and devise protocol for mitigation treatments – SFF on mitigation with on-farm monitoring
   Qualitative on-farm research
   Accompanied by robust quantitative research
3. Quantify economic/environmental impact of soil hydrophobicity
4. Quantify the water quality impact at the national scale; link to soil water quality via Regional Councils
5. Study hydrophobicity in relation to water use efficiency and rainfall management
6. Identify and introduce soil quality indicator for soil hydrophobicity
7. Fertiliser industry: Area of soil amendments (mitigation of soil hydrophobicity) as a new growing industry
8. Prepare a factsheet on soil hydrophobicity
9. Circulate presentations to all participants
10. Submit a contribution to NZ Grasslands Association conference; *Countrywide* contribution?

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Appendix 1 The influence of SWR on surface infiltration rates

A1.1 The importance of capillary and gravitational forces for surface water infiltration into soils with SWR

Several formulations exist to describe surface infiltration rates. The model of Green and Ampt (Green and Ampt 1911) gives the infiltration rate i [LT^{-1}] as a function of time t [T] by:

$$i(t) = K_{fs}\left[\frac{h_o + \psi_f}{z_f} + 1\right], \qquad \text{(A1)}$$

where K_{fs} is the field-saturated hydraulic conductivity [LT^{-1}], h_o [L] is the ponding depth , ψ_f [hPa] is the wetting front suction, and z_f [L] is the depth of the wetting front. If the precipitation rate p (t) [LT^{-1}] exceeds i(t) run-off is generated that might lead to overland flow.

Two forces control infiltration and drainage: capillarity associated with the nooks and crannies of the soil's porous networks, plus gravity which attracts water downwards towards the centre of the Earth. As a rule of thumb, flow in fine-textured and in very dry soils is dominated by capillarity, and for coarse-textured and wet soils the dominant force is gravity and can be approximated by the hydraulic conductivity. In the Green and Ampt model, the first term on the left hand side of Eq. 1 accounts for capillary and the second term for gravitational forces.

A1.2 Soil properties governing the capillarity-dominated surface infiltration

The soil properties that dominate the capillary forces (ψ_f in Eq. A1) can be derived from the capillary rise equation:

$$\psi_f \approx \frac{2\sigma_{wa}\cos(CA)}{\rho_w\, g\, R}, \qquad \text{(A2)}$$

where σ_{wa} [J m^{-2}] is the surface tension at the water-air interface [typically 0.0725 J m^{-2}], CA [°] is the average contact angle between the soil particle surfaces and the water-air interfaces, ρ_w is the specific density of water [typically 10^3 kg m^{-3}], g is the acceleration due to gravity [9.81 m s^{-1}], and R [m] is the geometric mean radius of the air-filled soil pores. Generally, in soils only CA and R vary in Eq. 2. Therefore, they govern the capillary forces of infiltration. What soil properties can be used as indicators for CA and R?

A1.3 Indicators for capillary-dominated surface infiltration

If the soils are hydrophilic (CA = 0) the effect of the contact angle can be neglected. Then, ψ_f depends only on the geometric mean radius of the air-filled soil pores that can be estimated from the soil texture (Rawls and Brakensiek 1989). It is standard practice to use the soil texture as an indicator for ψ_f (Beven 2001). We suggest that soil texture thus would be an appropriate SQI for the capillary-dominated infiltration in hydrophilic soils (Figure A1).

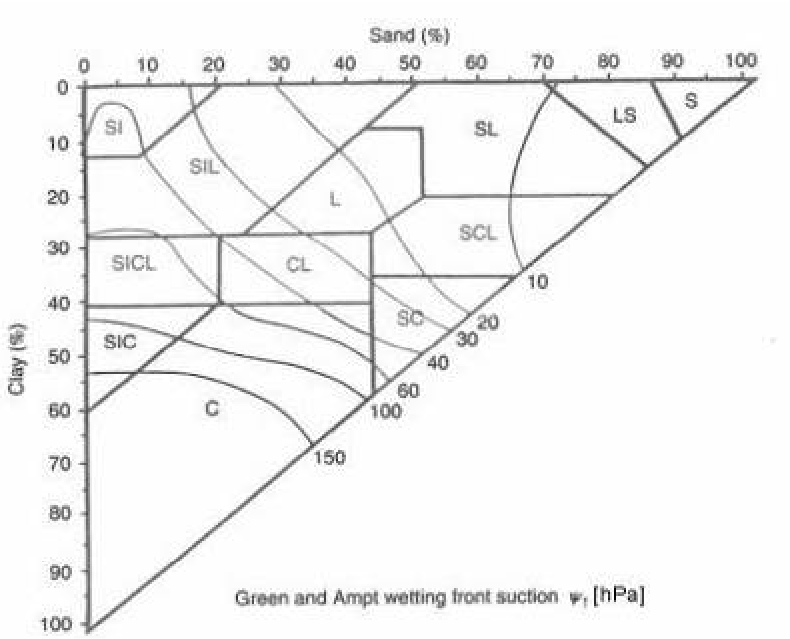


Figure A1: Estimation of the wetting front suction using the soil's texture. The figure is based on the work of Rawls and Brakensiek (1989) and was taken from Beven, 2001.

Water repellency (CA > 0) reduces the capillary forces, and was observed in many soils across NZ (Wallis *et al.* 1991). For example, a CA of 80° reduces ψ_f by about 83%. In hydrophobic soils with CA > 90° water will only infiltrate if ponding occurs. In that case, water would first enter the largest pores. We conclude that large CA's could drastically increase surface run-off.

Water repellency is a very dynamic soil property (Bachmann *et al.* 2007; Deurer and Bachmann 2007). The CA alone cannot predict a soil's complex water repellency behaviour: Water repellency occurs only once the soil has dried out below a ***critical water content*** (Bachmann *et al.* 2007; Dekker *et al.* 2001a). Water repellency has a ***site-characteristic persistence*** (e.g., after the start of rewetting) (Bachmann *et al.* 2007; Doerr and Thomas 2000). Therefore, the duration of its impact is variable and can last from seconds to weeks. Currently, the critical water content and the site-characteristic persistence of water repellency are difficult, time-consuming and expensive to measure. Therefore, they are not suitable as SQI's.

Another issue is the scale dependency of water repellency. Hydrophobicity might be a severe problem at the paddock or farm scale for triggering surface run-off. However, at the same time, hydrophobicity might be poorly correlated with catchment-scale run-off (Doerr *et al.* 2003). Currently, it is not clear how to up-scale hydrophobicity to predict its correlation with surface run-off at a larger scale.

We recommend measuring only the CA of the dry soil as an SQI for the potential hydrophobicity. By this, we could predict, for example, which areas have a high risk for surface run-off after a dry summer (e.g., some regions in Hawke's Bay). First measurements are under way.

Appendix 2 Programme of the workshop

Workshop: Towards a better understanding of the causes, effects and remediation of soil hydrophobicity

Date: Wednesday 24 February, 2010
Venue: Fitzherbert Seminar Room,
AgResearch Grasslands, Palmerston North

10.00 Morning tea

10.15 Welcome and Introduction (Grant Douglas, AgResearch)

10.20 Goals of workshop (Markus Deurer, Plant & Food Research)

10.25 Regional Council perspective (Ian Millner, Hawke's Bay Regional Council)

Part 1 - Understanding soil hydrophobicity

10.35 Overview: What is soil hydrophobicity and why do we bother about it? (Markus Deurer, Karin Mueller, Plant & Food Research)

11.10 What substances cause hydrophobicity in soils? (David Horne, Massey University)

11.30 Impact of soil hydrophobicity on pasture growth, farm finances and the proposed strategies for its mitigation. (Mike Slay, AgTechnology & Advisory Service)

11.50 Group discussion (chaired by Alec Mackay, AgResearch): General knowledge and understanding of problem. What observations have you made in your region (e.g. patchy pasture growth) that might be explained by soil hydrophobicity?

Part 2 - Measurement and monitoring of soil hydrophobicity

12.30 Lunch; displays on measurement of soil hydrophobicity: Hands-on demonstration of the impact of soil hydrophobicity (e.g. lack of water infiltration, enhanced run-off). (Karin Mueller, Markus Deurer, John Carter, Carlo van den Dijssel, Plant & Food Research)

1.30 Monitoring soil hydrophobicity: A survey of soil hydrophobicity in the North Island and a first estimate of its economic and environmental impact. (John Carter, Plant & Food Research)

Part 3 - Mitigation of soil hydrophobicity

2.00 The occurrence of hydrophobic soils in golf course fairways and its management and control. (Geoff Walker, TurfCleanNZ)

2.20 Group discussion (chaired by Grant Douglas, AgResearch): Where to go from here? Knowledge gaps, funding strategies and options, actions and timetable.

3.10 Workshop close (Markus Deurer, Plant & Food Research)

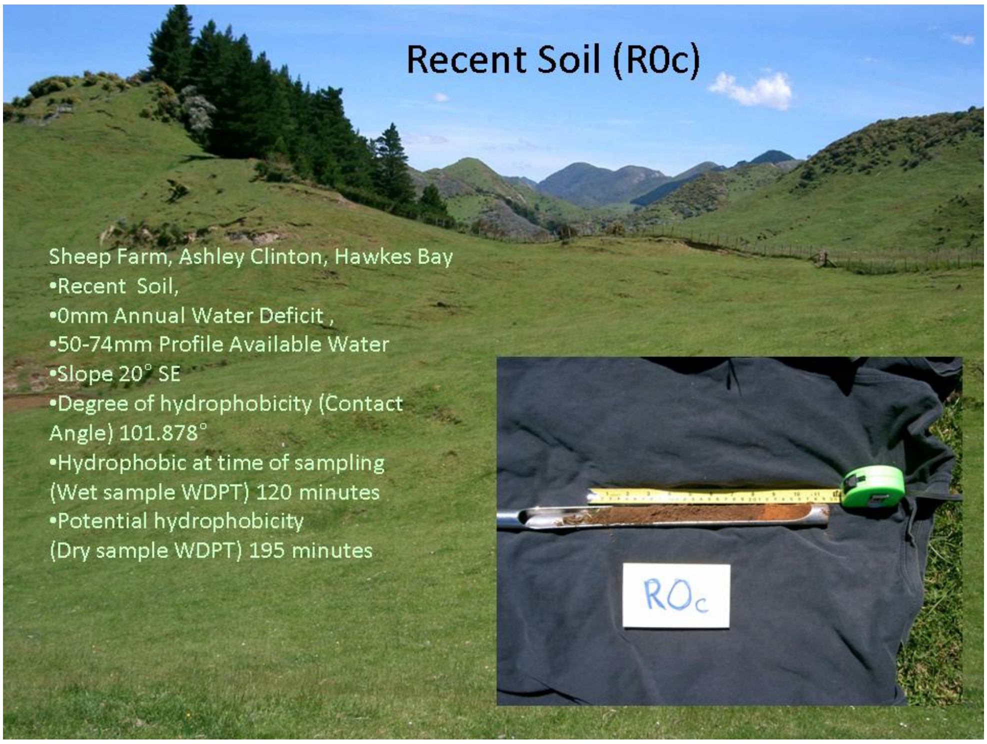
3.15 FINISH

Appendix 3 Handouts for the workshop demonstrations

A3.1 Background information on the soils used for the ‘Measurement of the persistence and degree of soil hydrophobicity’ demonstration

A3.1.1 Organic soil

A3.1.2 Recent soil



A3.1.3 Brown Soil

A3.2 Hand-out for the 'Reduction of water infiltration rate by soil hydrophobicity' demonstration

A3.2.1 Infiltration of water and ethanol into water repellent soils

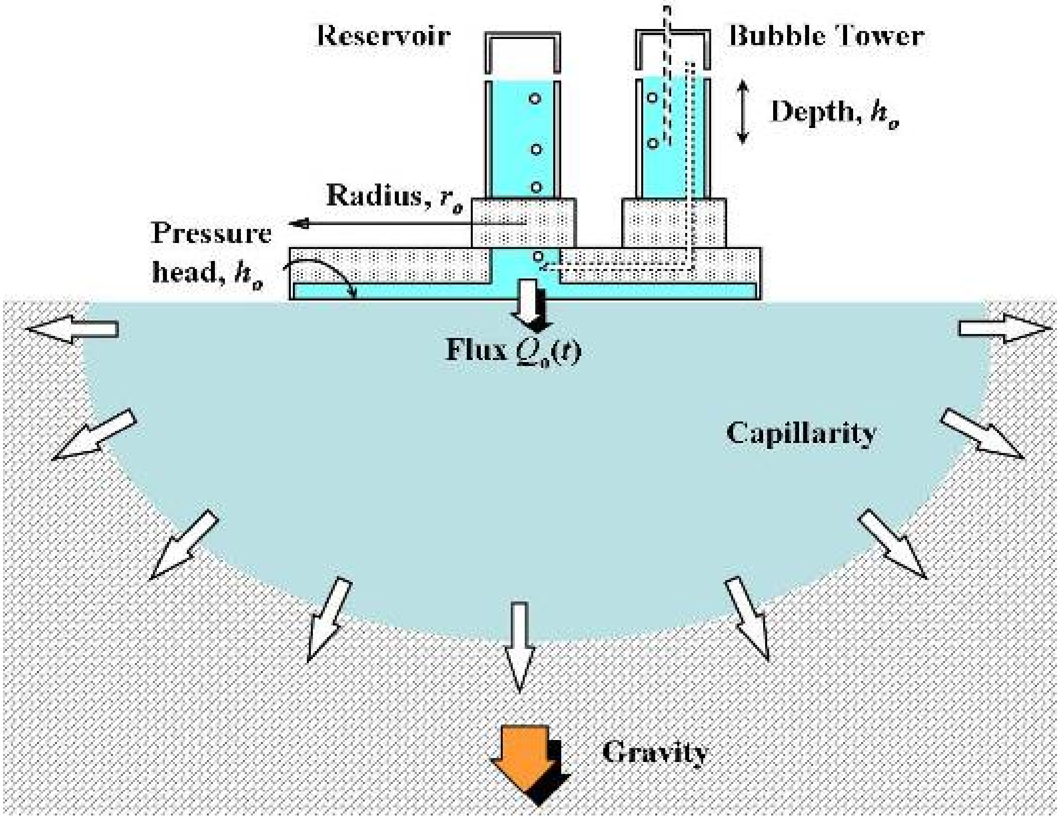


Figure A3.2.1 Schematic cross-sectional view of a tension infiltrometer showing its principles of operation. The infiltrometer is set at pressure head h_o and both capillarity (multi-dimensionally) and gravity (vertically) draw water from the reservoir into the soil at flux density Q (mm hr^{-1}). (Taken from Deurer et al., 2007)

Measurement method: Tension Infiltrometry

Two forces control infiltration into, and drainage through soil: capillarity associated with the nooks and crannies of the soil's porous networks, plus gravity which attracts water downwards towards the centre of the Earth. Flow in fine-textured soils is dominated by capillarity, and for coarse-textured soils the dominant force is gravity. Sorptivity is an integral measure of the soil's capillarity, and hydraulic conductivity is a measure of the ease with which water can pass through a soil under a given total potential gradient. Tension infiltrometers are devices that can be used to measure the soil's capillary and conductive properties (Fig. 1) in the laboratory and in the field (Fig. 2).

Comparison of water versus ethanol infiltration in water repellent soils

Soil water repellency can have a major impact on the infiltration of water. We measure the infiltration rates of water and ethanol near saturation at the soil surface. The water infiltration rates are affected by soil water repellency and represent the actual infiltration rate. The ethanol infiltration rates are not affected by soil water repellency and represent best the potential infiltration rate (e.g. in the absence of soil water repellency).

A comparison of water and ethanol infiltration rates is a practical measure for the impact of soil water repellency on the soil's capacity for water infiltration. If the water infiltration rate is below the rainfall rate water will run off.

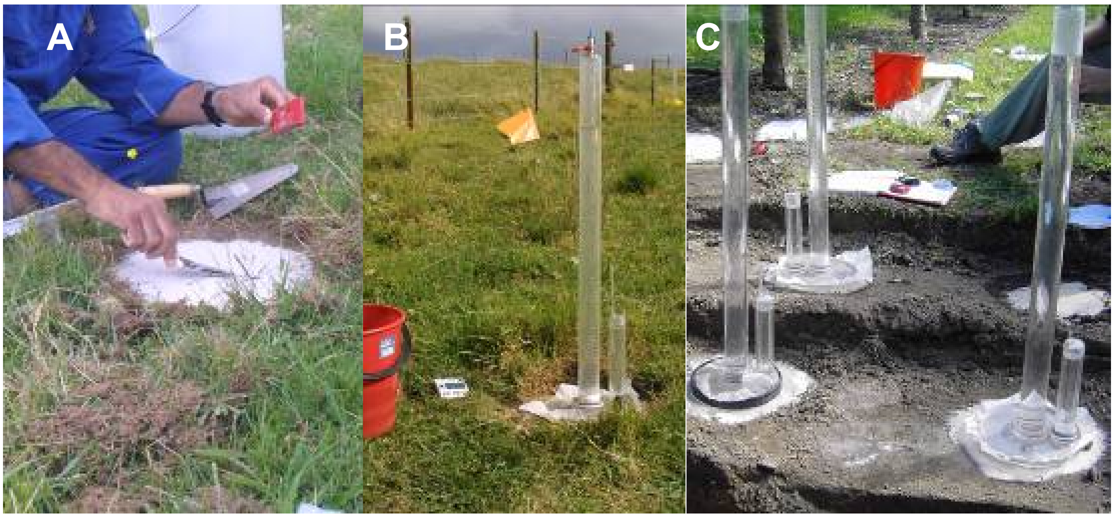
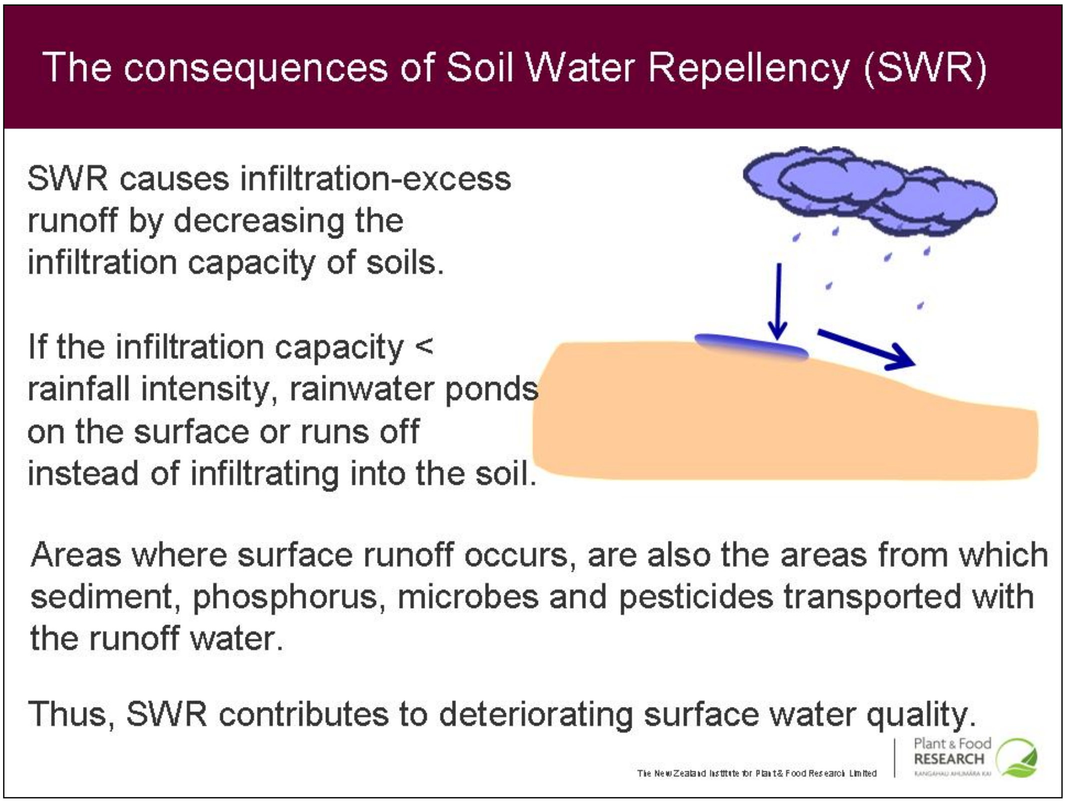


Figure A3.2.2 The use of tension infiltrometers in the field. **A**) Preparation of the contact sand as the infiltration surface atop the undisturbed soil. **B**) Measurement of the infiltration rate at the surface. **C**) Multiple and simultaneous measurement of infiltration rates at several depths in a soil profile. (Taken from Deurer et al., 2007).

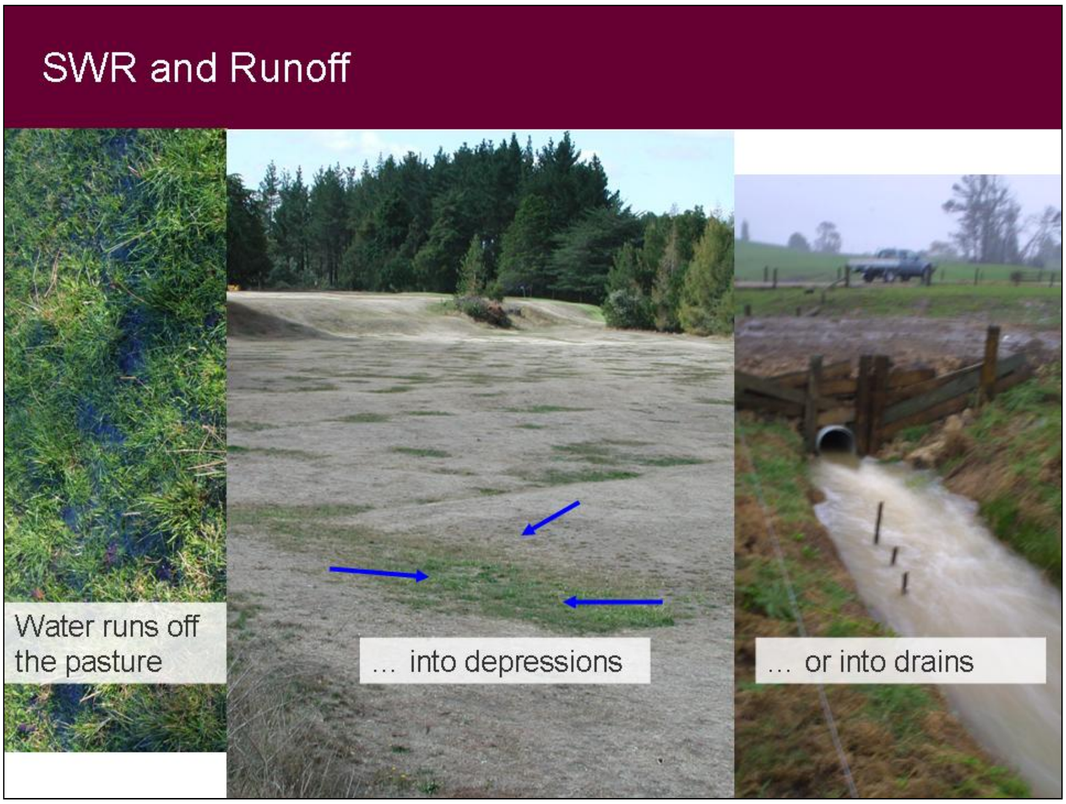
Deurer M, Clothier BE, Green S, Gee GW (2007) Infiltration rate, hydraulic conductivity, and preferential flow. In 'Soil Science: Step-by-step Field Analyses'. (Eds SD Logsdon, D Clay, D Moore, T Tsegaye). (Soil Science Society of America: Madison, WI).

A3.3 Hand-outs for the 'Generation of run-off and overland flow by soil hydrophobicity' demonstration

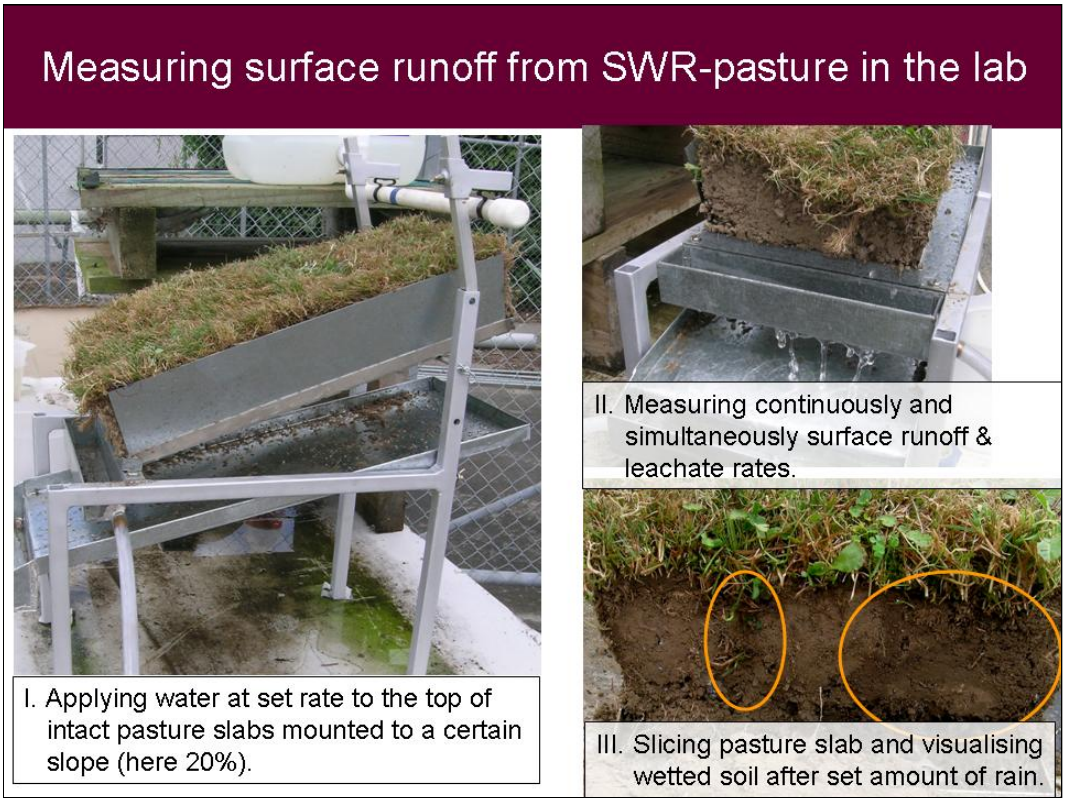
A3.3.1 The consequences of SWR



A3.3.2 SWR and run-off



A3.3.3 Measuring surface run-off from SWR-pasture in the lab



Appendix 4 List of workshop participants

First name	Surname	Organisation
Alec	Mackay	AgResearch
Grant	Douglas	AgResearch
Mike	Slay	AgTechnology and Advisory Service
Mohammad	Zaman	Ballance Agri-Nutrients
Sharn	Hainsworth	CPG NZ Ltd
Matthew	Taylor	Environment Waikato
Brendan	Powell	Hawke's Bay Regional Council
Ian	Millner	Hawke's Bay Regional Council
Janine	Dunlop	Hawke's Bay Regional Council
Monique	Benson	Hawke's Bay Regional Council
Nicolas	Caviale-Delzescaux	Hawke's Bay Regional Council
Warwick	Hesketh	Hawke's Bay Regional Council
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