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AN INVESTIGATION OF WATER REPELLENCY IN A RANGE OF NEW ZEALAND SOILS

A thesis presented in partial fulfilment
of the requirement for the degree of
Doctor of Philosophy in Soil Science
at Massey University, New Zealand.

by
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ABSTRACT

The severity of water repellency was investigated on a wide range of agricultural, horticultural and turf soils in New Zealand. All the soils studied had some degree of repellency, regardless of texture or land use. Techniques for repellency measurement and amelioration were evaluated and the organic component responsible for repellency development investigated. The temporal and extreme spatial variability of repellency expression was quantified using geostatistics.

The 'repellency index' (RI) based upon soil intrinsic sorptivity was developed and evaluated on 14 New Zealand soils. The RI measured undisturbed cores of all the soils water repellent at field moisture conditions and was more sensitive than the MED or water drop penetration time (WDPT) tests. The RI was used to demonstrate that repellency reduced the short-time infiltration rate, i of all the soils by approximately an order of magnitude, including those which appeared to wet normally (i.e. low WDPT). Calculations identified that the reduction in i would be hydrologically significant under intense rainfall and many irrigation systems.

Investigation of a development sequence of yellow-brown sands (Aquic Udipsamments) revealed maximum repellency in $<$ 130 y old Waitarere sand, which had the lowest level of organic carbon. Repellency was also severe in the Motuiti and Himatangi sands (c. 500 y) but declined in the Foxton (1600 - 6000 y) and Koputaroa (10000 - 25000 y) soils. While water repellency (measured with the Molarity of Ethanol Droplet, MED test) of the Himatangi sand profile was correlated with organic carbon content, this was not the case with the other soils. Organic matter composition is a more likely determinant of the degree of repellency than organic matter quantity *per se*.

Spectroscopic examination of extracts removed from Himatangi sand by an *iso*-propanol/ammonia mixture using a soxhlet apparatus indicated a range of long chain organic compounds comprising esters and fatty acids as the cause of repellency.

The spatial variability of volumetric soil water content (θ) to 200 mm depth at two

adjacent sites (A and B) of Himatangi sand, each c. 860 m^2, was studied with geostatistical techniques. At both sites θ varied isotropically and generally followed a normal distribution. Variograms of θ changed over time and were not transferable between the two sites, although there was evidence of drift in the mean at site B. At site A, compared to an October analysis, in summer the coefficient of variation (C.V.) of θ increased and the range of θ spatial dependence, a decreased. Irrigation of both site A and B with a travelling boom slightly increased C.V.(θ), markedly increased the semivariance and slightly decreased $a(\theta)$ at site A. When a wetting agent was applied prior to irrigation of site A the C.V.(θ) halved, $a(\theta)$ increased and the θ increase was improved by 63 % over irrigation of site A and 206 % over irrigation of site B.

Agitation of soil samples reduced repellency significantly, however the effect was somewhat reversible and field cultivation could be precluded by the degree and depth of the repellent topsoil. Soil wetting agents increased grass establishment and growth in both glasshouse and field experiments. In the glasshouse, wetting agent performance was not affected by delayed initial irrigation, however short irrigation return intervals improved plant growth in both untreated and wetting agent treated soil.

A survey of golf courses throughout New Zealand found that repellency was a major management problem. Soil cores were removed from areas of greens displaying repellency symptoms ('dry patch') and from areas of compatatively healthy turf. No significant difference was found between the MED profile or the thatch content of the dry patch and non-dry patch cores. Dry patch areas were found to match the poorly irrigated areas of a green using a simple 'catch-can' test, which indicated that irrigation uniformity affected repellency expression in turf.

ACKNOWLEDGEMENTS

I am most grateful to my supervisors, Dr. Dave Horne, Dr. Dave Scotter and Mr. Keith McAuliffe for their untiring assistance, advice and encouragement during the course of this work. In particular I wish to thank my chief supervisor, Dr. Dave Horne, who has always had time for discussion and been ready to assist with field and laboratory work. I have also had the first-class technical assistance of Messrs. Sean O'Conner, Hugh Furlong, Ian Furkert, Alistair Picken, Martin Eggels, Ross Wallace and Mrs Heather Murphy. Our secretaries, Mrs. Ann Rouse and Mrs Colleen Manson have typed a number of the papers which comprise this thesis.

My family, and in particular my wife Jane have always been most supportive during both my undergraduate and postgraduate studies. I have also been blessed with many friends who have provided encouragement and empathy along the way.

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CHAPTER ONE: INTRODUCTION AND LITERATURE REVIEW

1.0 INTRODUCTION

Soils which 'repel' or resist water entry cause major problems for management in a wide range of situations from pastoral agriculture to sports turf. Water repellency of soils is both a complex and inadequately recognised problem. The complexity of repellency rapidly becomes apparent to the scientist or land manager, and has made studies of the problem difficult. Thorough investigations of repellency must be broad in approach, encompassing almost all features of the soil science discipline. As to ignorance of repellency, fault lies with the scientific community, because many managers of repellent soils are painfully aware of its significance.

Interest in repellency research at Massey University dates back to 1987 with an irrigated dairy pasture soil, the Himatangi sand (Wallis 1987). In this study the Himatangi sand has been used in field, laboratory and glasshouse studies to evaluate options for repellency control, including application of soil wetting agents, irrigation, and cultivation. Efforts to ameliorate repellency with wetting agents in field trials were of limited success, primarily because of the extreme spatial variability of repellency. The wetting agent trials with the Himatangi sand led to research of sports turf, since the greatest proportion of wetting agents were known to be used in the industry. As a result of the work with the Himatangi sand and sports turf soils, a number of practical recommendations have been made to help the farmer and groundsperson manage repellent soils.

It became obvious that to fully elucidate the nature of repellency expression a change in direction was required, involving a more thorough study of mechanisms and processes. In the New Zealand context it was planned to address four key questions, namely: how many soils have water repellency; how can repellency be best measured; what causes repellency, and how can the spatial and temporal variability of repellency be characterised and explained?

The Himatangi sand forms one soil in a development sequence of aeolian sands which

range in age from 0 to c. 25 000 years. The development sequence was seen as an ideal opportunity to study the development of repellency with time. Within the age groups represented in the development sequence, the effects of soil topographical position and plant cover upon repellency were also studied. Both the severity of repellency and the organic component(s) responsible for repellency were investigated in this study.

Standard statistical analysis and geostatistics, a comparatively new technique to soil research were employed to quantify the spatial variability of the soil water content in the Himatangi sand. Soil water content was measured as a reflection of the effect of repellency upon infiltration of rain and irrigation water.

Limitations with existing repellency measurement techniques became evident during the course of the repellency research with the aeolian sands and other soils. Development and evaluation of the intrinsic sorptivity repellency index improved understanding of the problem and affected perceptions regarding repellency severity and occurrence.

The nature of the work incorporated in this thesis has lent itself to subdivision along the lines of separate papers. Therefore the chapters have been written essentially as papers, however introductory sections have been written for each chapter to improve the cohesiveness and readability of the thesis. To date, four papers have been published in refereed journals, including two on the Himatangi sand:

Wallis, M.G., Horne, D.J. and McAuliffe, K.W. 1990a. A study of water repellency and its amelioration in a yellow brown sand. 1. Severity of water repellency and the effects of wetting and abrasion. *New Zealand Journal of Agricultural Research 33:* 139-144.

Wallis, M.G., Horne, D.J. and McAuliffe, K.W. 1990b. A study of water repellency and its amelioration in a yellow brown sand. 2. The use of wetting agents and their interaction with some aspects of irrigation. *New Zealand Journal of Agricultural Research 33:* 145-150.

and two on the repellency index:

Tillman, R.W., Scotter, D.R., Wallis, M.G. and Clothier, B.E. 1989. Water repellency and its measurement using intrinsic sorptivity. *Australian Journal of Soil Research 27:* 637-644.

Wallis, M.G., Scotter, D.R. and Horne, D.J. 1991. An evaluation of the intrinsic sorptivity water repellency index on a range of New Zealand soils. *Australian Journal of Soil Research 29:* 353-362.

A further four papers have been submitted for publication, including the following review of the repellency literature.

1.1 SOIL WATER REPELLENCY

M.G. Wallis and D.J. Horne
Department of Soil Science, Massey University, N.Z.

An invited paper submitted to Advances in Soil Science.

I. INTRODUCTION

Water repellent soils exhibit hydrophobic properties when dry, resisting or retarding water infiltration into the soil matrix (Brandt 1969a). Infiltration rates may be reduced by an order of magnitude, even in soils which visually appear to wet 'normally' (Wallis *et al.* 1991). Repellent soils have been reported in many countries (DeBano and Letey 1969) and may occupy large areas, such as the sandy soils of South and Western Australia (Bond 1969a). However severe repellency is relatively uncommon, and hence the condition is generally regarded as interesting but inconsequential. Indeed, the assumption of non-water repellent behaviour is the norm in soil physics (Philip 1969).

Over the years a number of soil scientists have suggested that repellency may be more widespread than is commonly acknowledged (Bond 1964; Gilmour 1968; DeBano 1969b; Marshall and Holmes 1979; Nakaya 1982). Wallis *et al.* (1991) evaluated a sensitive technique for repellency measurement (Tillman *et al.* 1989) on 14 New Zealand soils which ranged in texture from sand to clay. All the soils were found to be repellent at field moisture conditions, which led Wallis *et al.* (1991) to suggest that repellency is the norm rather than the exception, with the degree of repellency variable. Furthermore it was demonstrated that repellency would affect the hydrological balance of all the soils under heavy summer rainfall and many irrigation systems.

A large body of repellency research exists. As early as 1910, Schreiner and Shorey referred to repellent soils in California. Jamison (1945) cited 'large bodies of difficultly

wettable soil which remained unwetted even during the rainy season' under Florida citrus trees. DeBano (1969a) described the 1960s as a decade of increasingly widespread interest in the problem of soil wettability. Much research was conducted at the University of California, Riverside, where an international conference was held on the subject (DeBano and Letey 1969). Research in California remained active throughout the 1970s and interest spread to other states and countries. Repellency has now been studied in natural soils, where it may be induced by fire (DeBano *et al.* 1976), in coal mine spoils (Miyamoto *et al.* 1977; Richardson and Woollenhaupt 1983) and in sports turf where it is a problem in numerous countries (Charters 1980; Shiels 1982; Danneberger and White 1988; Wallis *et al.* 1989a,b). Although research into repellency has waned somewhat over the last two decades, there are now over 150 papers on the topic which have not been reviewed.

The purpose of this review is fivefold:

(i) To draw attention to the hydrologic and agronomic problem of repellency;

(ii) To identify techniques for repellency measurement and discuss their relative merits;

(iii) To summarise the processes by which repellency is thought to develop;

(iv) To discuss measures for ameliorating repellency;

(v) To identify future research priorities.

Most importantly, it is hoped that this review will stimulate debate and research in an under-recognised field.

II. THE EFFECTS OF REPELLENCY

A. Infiltration, Plant Growth, Runoff and Erosion

The primary effect of repellency is a reduction in the rate of water infiltration. In contrast to 'wettable soils', in which infiltration rates decline during water penetration, the infiltration rate of severely repellent soils is slow during the initial phases of infiltration and increases with time (DeBano 1969c; Bond 1964; Wallis *et al.* 1991). When the repellent layer is at depth, which may occur after fire, infiltration markedly decreases when the wetting front approaches the repellent layer (DeBano 1969a).

DeBano (1971) studied infiltration into repellent soil and ignited (nonrepellent) soil. Horizontal infiltration was 25 times slower in the repellent soil, which also displayed a more diffuse wetting front - i.e. the repellent soil did not wet completely when the wetting front passed. He found that the diffusivity of repellent soil was smaller than that of nonrepellent soil at all water contents. The largest differences in diffusivity occurred at both the lower and higher water contents. DeBano (1971) suggested that the substances in the soil responsible for repellency had the greatest effect on water movement at low water contents, but could not explain the large diffusivity difference at high water contents.

Repellency is most strongly expressed as soil dries (Bond 1964; King 1981; Wallis *et al.* 1990a). However King (1981) and Wallis *et al.* (1990a) found that repellency severity declined somewhat when the soils became very dry (fig. 1.1). Wallis *et al.* (1990a) suggested that the decreased repellency severity was due to molecular conformational changes in the organic matter responsible for repellency (section IV.A.) however the mechanism is unknown.

Wallis *et al.* (1990a) found that dry, elevated areas of repellent sand had an infiltration rate of c. 37 mm h^{-1} compared to lower-lying, moist areas of soil with an infiltation rate of c. 204 mm h^{-1} (fig. 1.2). Measurement of the repellent soil using the 'Repellency Index' (section III.B) has shown that the rate of water infiltration may decline to less than 1 % of the 'potential' rate if the soil was nonrepellent (Wallis *et al.* 1991).

Reduced water infiltration due to repellency may affect the available soil water for seed germination and plant growth (Bond 1972; McGhie 1983; Wallis *et al.* 1990b) (fig. 1.3). Bond (1972) measured delayed, reduced germination of barley on repellent sands in Australia which decreased the average grain yield to 50 % of that on less repellent sites. Shepherd and Wallis (unpub. data) measured a yield effect of similar magnitude in a repellent humic clay (Fluvaquentic Haplaquoll) under maize in New Zealand.

The reduction in water infiltration has important hydrological implications (John 1978). Water repellency may be responsible for increased surface water redistribution and erosion on many hill and steepland soils, particularly following heavy summer and autumn rainfall events (Wallis *et al.* 1991). Osborn *et al.* (1964) found that accelerated rill erosion

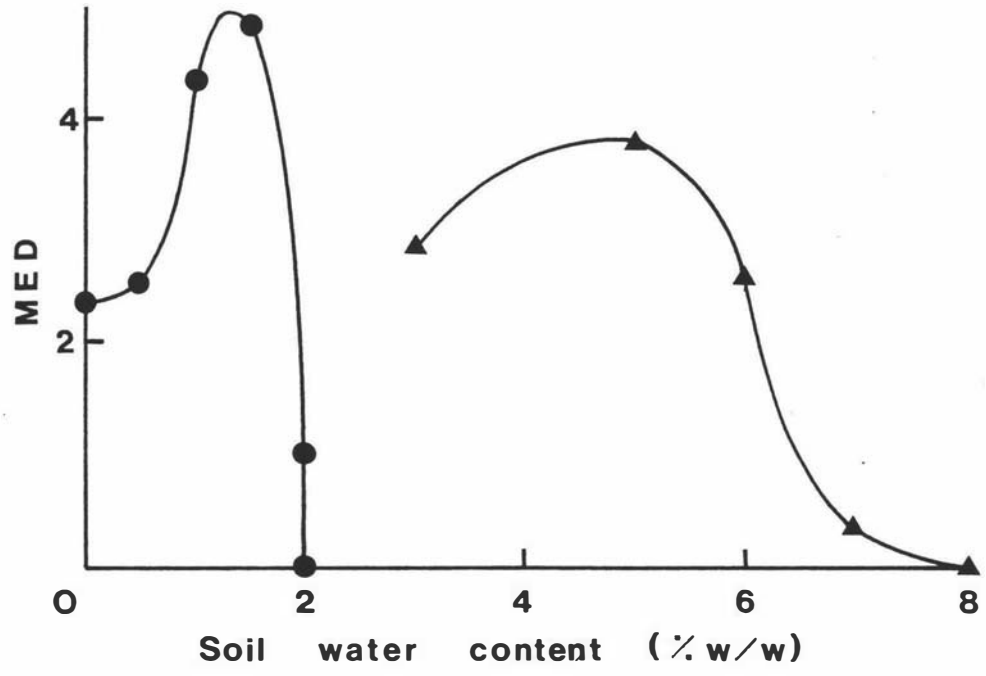


Figure 1.1. Variation of soil water repellency (Molarity of Ethanol Droplet, MED) with soil water content. (▲ = Himatangi sand, after Wallis *et al.* 1990a; ● = sand 'B' following 168 h moistening at 9 °C, after King 1981). Curves fitted by hand.

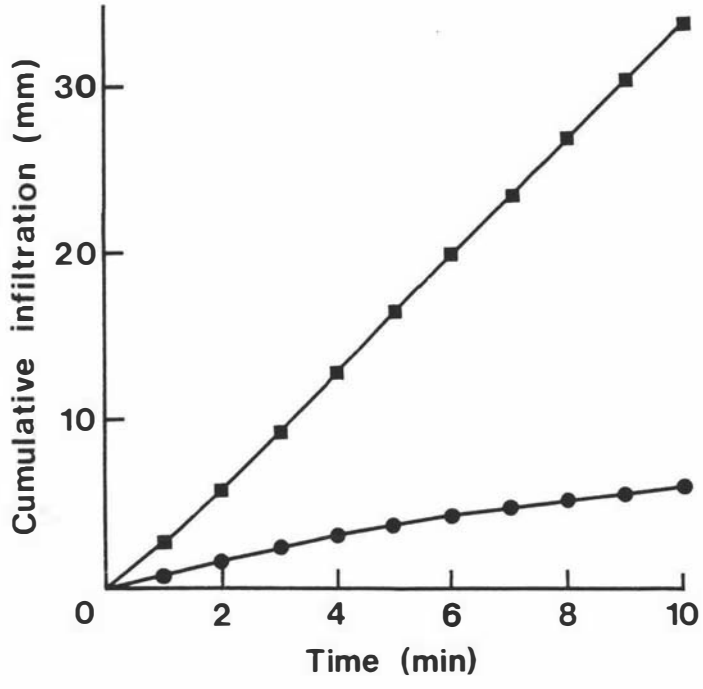


Figure 1.2. Mean water infiltration into repellent (●) and less repellent (■) Himatangi sand from a + 10 mm head disc permeameter (3 replicates per site; L.S.D.(0.01) = 10.6). After Wallis *et al.* (1990a).

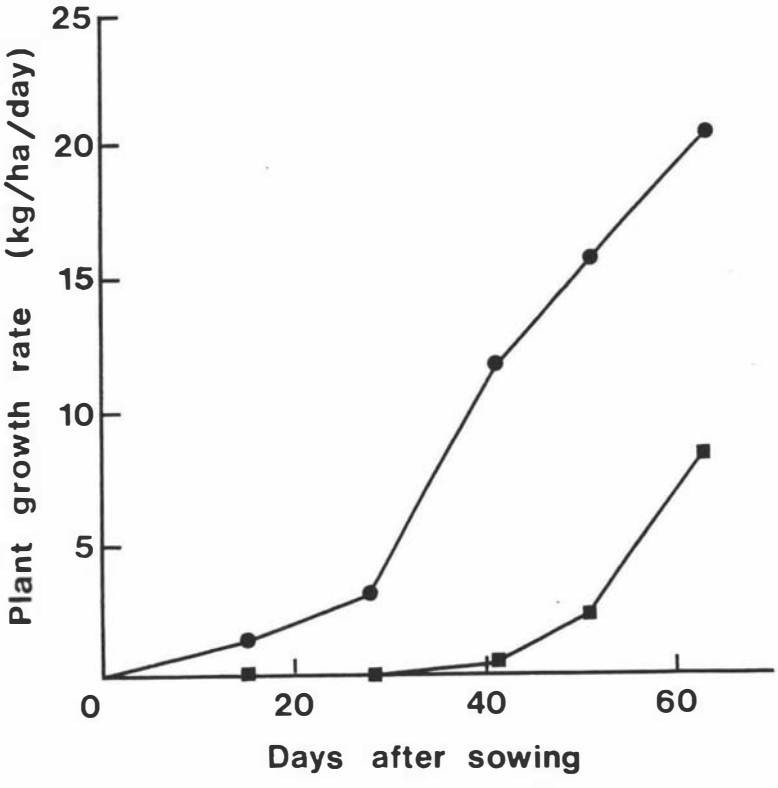


Figure 1.3. Growth rate of ryegrass (*Lolium perenne*) sown in glasshouse trays of water repellent Himatangi sand (control, ■) compared to trays treated with a nonionic wetting agent (●). L.S.D.(0.01) = 2.03, 1.73, 6.17, 7.13 and 6.52 kg ha^{-1} day^{-1} at 15, 28, 41, 51 and 63 days respectively. After Wallis *et al.* (1990b).

occurred on repellent plots compared to plots treated with a wetting agent to increase infiltration (section V.C). They also noted significantly lower vegetative establishment on the repellent soil. John (1978) found that accelerated erosion caused by heat-induced repellency (section IV.F) could be a serious problem on normally nonrepellent Andisols in New Zealand. The influence of repellency upon runoff and erosion deserves more attention, considering both the on-site and downstream consequences.

The creation of synthetic repellent soil to artificially increase water runoff has been suggested for areas which suffer from a seasonal water deficit (Fink and Myers 1969). They found that a spray application of sodium methyl silanolate in a small field trial produced repellency which caused 94 % of rainfall to run off from 25 storms over 5 months compared to 41 % from untreated soil. Fink (1970) pointed out that an effective material should also stabilise the soil or be compatible with a soil stabiliser, must be durable against weathering and be inexpensive and easy to apply. While Fink (1976) found that a mixture of a petroleum resin and parrafin wax was stable and durable in laboratory tests, the economics and practicality of field application has yet to be evaluated.

B. Soil Water Movement and Aggregate Stability

Water movement within soil may also be affected by water repellency. Raats (1973) noted that a repellent soil may cause wetting front instability and lead to the development of preferential flow pathways. Hendrickx *et al.* (1988a,b) used a field iodine-staining technique to show that repellent Netherland soil developed preferential flow paths for water and solute movement. As a consequence, the repellent soil had a greater potential for groundwater contamination. Wallis and Horne (unpub. data) have also found evidence of preferential flow pathways in repellent sand (fig. 1.4). Water repellency may be a significant but neglected factor in the development of models used to predict water and solute flow through soil.

Giovannini *et al.* (1983) found that the natural hydrophobic substances in a repellent clay loam appeared to behave as cementing agents of soil aggregates. The hydrophobic

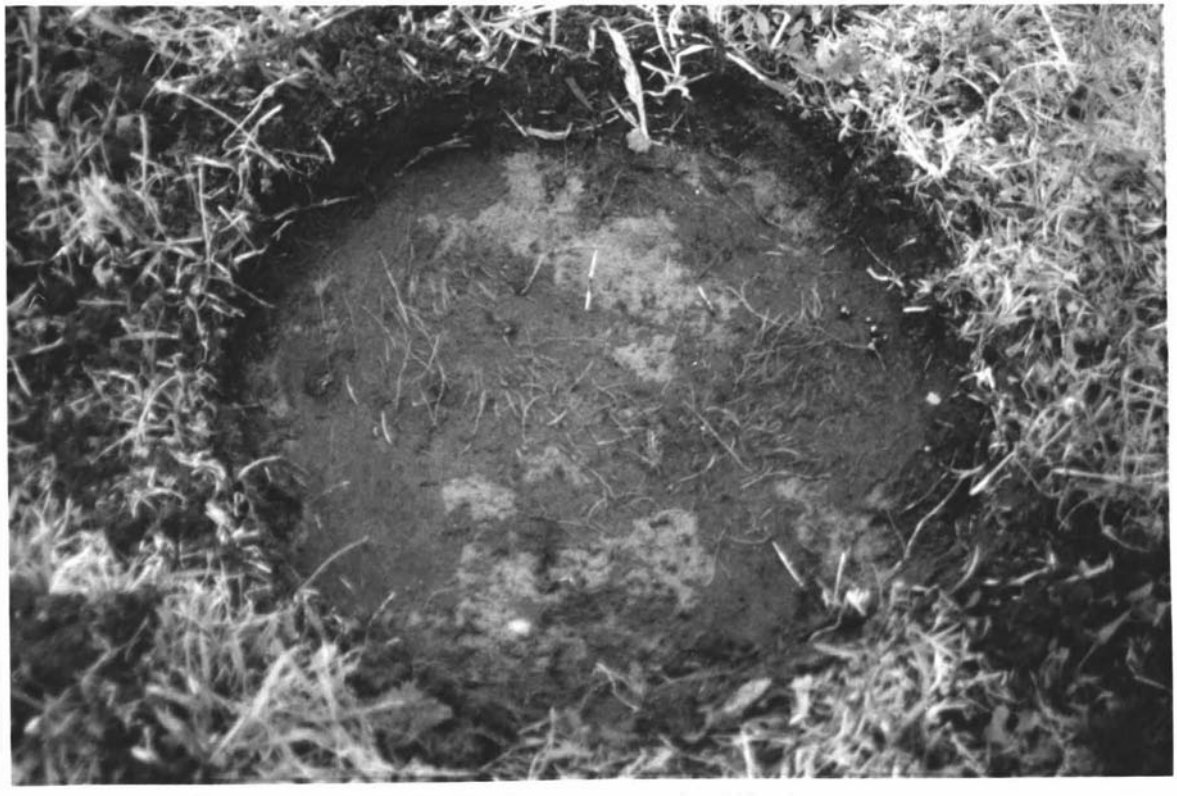


Figure 4. Apparent preferential flow pathways at 50 mm depth in water repellent Himatangi sand after water was ponded in a ring infiltrometer (diameter 400 mm). Note the high concentration of plant roots within the wetted soil (photo M.G. Wallis).

substances increased aggregate stability but prevented water from entering the aggregates, restricted infiltration and caused intense surface runoff. Synthetic repellent chemicals have been developed for engineering uses which exploit these properties (Brandt 1969b; Bozer *et al.* 1969). Certain hydrophobic chemicals stabilise soil by limiting water absorption. One such chemical is 4-tert-butylcatechol (TBC), which can make soils more easily compacted than in their natural state (Brandt 1969b). Presumably the cost of such chemicals has prevented their adoption by engineers.

The potential for increased aggregate stability of repellent soil to decrease problems with surface soil crusts was investigated in laboratory experiments with a clay loam (Rawitz and Hazan 1978). Mulches of coarse synthetic repellent aggregates reduced surface soil crusting, increased water infiltration and improved seedling emergence by 40 - 100 % compared to the control of bare soil. They pointed out that field-testing was necessary and that the procedure was expensive at the application rates evaluated.

Synthetic hydrophobic substances have also been used to reduce evaporation from soil. Lemon (1956) cited 1940s Russian research in which a 'naptha soap compound' rendered repellent and reduced evaporation by '6 or 7 times.' DeBano (1969a) cited a 15% reduction in evaporation from a sand which was made repellent with ammonium hydroxide extracts of chaparral litter.

In regions with severe water limitations, the use of repellent surface mulches for moisture conservation may prove viable, provided that the mulches may be manufactured simply and economically. Hillel and Berliner (1974), Fairbourn and Gardner (1975) and Rawitz and Hazan (1978) found that surface soil mulches of coarse repellent aggregates allowed adequate water infiltration but reduced evaporation to 5%, 73% and 80% of the control soils respectively. The coarse repellent aggregates (2 - 5 mm) actually increased water infiltration by allowing more rapid water movement through the interaggregate voids (Hillel and Berliner 1974). The effect of natural repellent soil layers upon evaporation is uncertain and warrants further research. Studies incorporating wetting agents have provided conflicting results (section V.C).

Water movement and root exploration may be restricted by repellent layers in the

reconstituted soil profile of coal mine spoils (Richardson and Woollenhaupt 1983). Synthetic water repellent layers have also been evaluated for the reduction of salt contamination in the reclamation of saline soils. De Jong (1983) found that layers of crude oil and soil prevented salt contamination of 'cover soil' in soil columns. The oil-soil mixture was found to be more effective than oil-alone at both preventing capillary rise from the saline soil and preventing downward movement of applied water into the saline soil. The technique requires field evaluation and is likely to be inappropriate in areas with a seasonal surplus of rainfall over evaporation due to water logging and associated problems in the cover soil.

III. DEFINITION AND MEASUREMENT OF REPELLENCY

In order to study repellency development or amelioration one must engage appropriate measurement techniques. Ideally the technique should be simple, inexpensive and provide a rapid quantitative measure of practical significance. Over the years many techniques have been developed to measure repellency, during which time the understanding and definition of repellency has evolved. This section discusses the inherent concepts and assumptions of each measurement technique and outlines their relative merits and limitations.

A. Contact Angle

Zisman (1964) provided a comprehensive review of the ways in which the nature of a liquid and a plane solid surface affect the resultant contact angle, *H* between them. The affinity or repellency of a solid surface for water originates from the attractive forces between them (adhesion). If adhesion exceeds the attraction between the individual water molecules (cohesion) then the water will spread out on the solid surface. Conversely, if adhesive forces are less than cohesive forces, the solid surface will repel water. When this happens the water "balls up" on the surface, forming a contact angle, *H*.

The mechanical equilibrium of a water droplet on a solid surface (fig. 1.5) was defined by

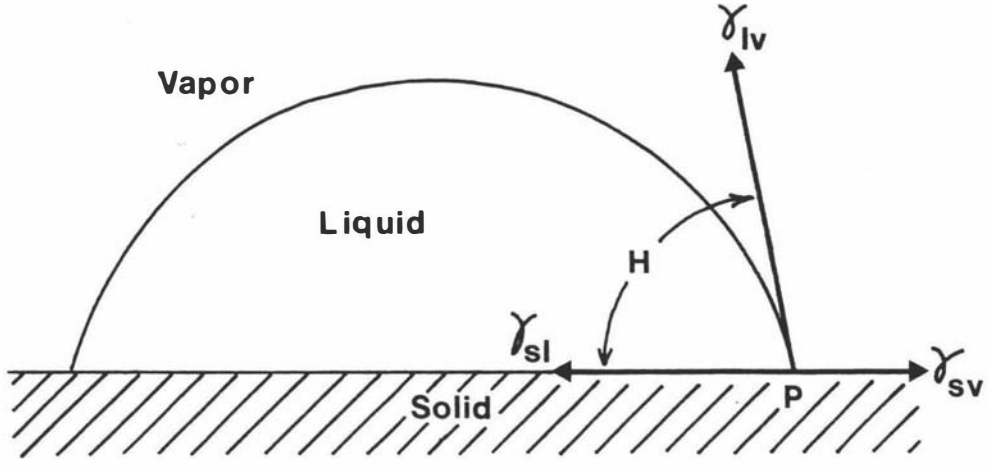


Figure 1.5. A liquid droplet at mechanical equilibrium on a solid surface. The forces (interfacial tensions, γ) about point P are balanced, as described in equation 1. After Zisman (1964).

Young (1805) as equation 1.

$$\gamma_{SV}-\gamma_{SL} = \gamma_{LV}\, cosH \qquad (1)$$

In which;

γ_{sv} = tension at the solid-vapour interface (N m^{-1})

γ_{sl} = tension of the solid-liquid interface (N m^{-1})

γ_{lv} = tension of the liquid-vapour interface; the liquid 'surface tension' (N m^{-1})

The liquid-solid contact angle can be geometrically measured for a plane solid surface. In porous media such as soils, the contact angle is conceptually the effective angle formed by a water meniscus in contact with the soil pore walls (DeBano 1969a). Bond and Hammond (1970), Fink and Myers (1969) and Mallik and Rahman (1985) directly measured the contact angle of water drops lying upon soil surfaces. The technique is only applicable to extremely repellent soils because in less repellent soils the water drop will penetrate and make geometric measurement impossible. However, even in extremely repellent soils, surface roughness and pore size distribution will affect the measured value (Letey 1969). At best, only an 'apparent contact angle' may be measured (Philip 1971). A full discussion of this aspect is given in section III.A.3.

1. Capillary Rise

Letey *et al.* (1962a) evaluated an infiltration and a capillary rise technique to indirectly determine the apparent contact angle, *H*. They assumed that the soil was characterised by cylindrical tubes and used Poiseuille's approximation in which the rate of solution capillary rise into a soil column is related to the physical properties of the solution, the effective pore radius, *r* (m) and *H*. The height of capillary rise at equilibrium, *h* (m) is represented by equation (2).

$$h = \frac{2\,\gamma\,\cos H}{\rho\,g\,r} \qquad (2)$$

where;

γ = surface tension of the solution (N m^{-1});

ρ = density of the solution (kg m^{-3});

g = acceleration due to gravity (m s^{-2}).

Neither r nor H are known. Ethanol was found to have the same H for all soil materials, which Letey *et al.* (1962a) assumed to be zero. Capillary rise of ethanol was used to calculate r, which was then used to calculate H when other solutions were used. Emerson and Bond (1963) used ignited soil samples to solve for r by assuming that the ignited sample had $H = 0^\circ$ when wet with water.

Letey *et al.* (1962a) found that the capillary rise technique produced reasonable and consistent measurements of H. They chose an arbitrary equilibrium time for maximum capillary rise of 24 hours. Nakaya *et al.* (1977b) immersed capillary tubes of ignited and nonignited soil in water to a depth of 300 mm and, after equilibration was reached, calculated H from the ratio of the height of capillary rise in the nonignited soil to that in the ignited soil. Hammond and Yuan (1969) pointed out that if H changes with the time of water contact, the equilibrium height of capillary rise would be influenced. Emerson and Bond (1963) were able to obtain an estimate of the initial H by plotting the rate of capillary rise over the first c. 15 minutes against the reciprocal of the height of rise and extrapolating to a zero rate of rise.

The general perception that soils with $H < 90^\circ$ should be considered 'nonrepellent', which was based upon water penetration into porous media (Watson and Letey 1970; section III.D), was challenged by Nakaya (1982). He contended that all soils with $H > 0^\circ$ are repellent to some degree. DeBano (1969a) pointed out that many researchers have reported H c. 50 - 60° in soils which appeared to absorb water normally, and he stated that 'wetting angles other than zero would be expected to affect the moisture movement processes in the soil governed by unsaturated flow'. Wallis *et al.* (1991) have

demonstrated that the repellency of such soils may be hydrologically significant (section III.B).

The major disadvantages of the capillary rise techniques are as follows:

(i) They are very time consuming. King (1981) reported that only 12 samples per person-day could be tested using Emerson and Bond's (1963) technique;

(ii) The methods of Letey *et al.* (1962a) and Nakaya *et al.* (1977b) do not indicate the initial H, since water is in contact with the soil for an arbitrary time period such as 24 hours (the 'reaction time', Zisman 1964). However, Emerson and Bond's (1963) method does allow an estimate of the initial H to be made.

(iii) The need to consider hysteresis effects; there is a difference between an advancing H and a receding H (Hammond and Yuan 1969).

(iv) Observations on porous media such as soils yield, at best, *apparent* contact angles which cannot be related directly to the actual contact angle at interfaces within the medium (Philip 1971). This limitation arises because the pore geometry affects the measured 'contact angle';

(v) They are not suitable for intact soil.

2. Infiltration

Letey *et al.* (1962a) evaluated an infiltration technique for H calculation which involved measurement of water and ethanol movement into soil columns. They found that the method worked well with soils but not with pure sands, which they suggested may have been due to sand pores trapping air while transmitting water downward. A constant but unspecified supply potential was used for the infiltration technique. A further limitation of the technique which was recognised by Letey *et al.* (1962a) was the measurement of

wetting front positions with the implicit assumption that the soil or sand was saturated behind the front. DeBano (1971) found that repellent soils have a more diffuse wetting front than nonrepellent soils.

3. Intrinsic Diffusivity and Sorptivity

Philip (1957) developed the theory of intrinsic diffusivity and sorptivity (equations 3 and 4).

$$D^*(\theta) = D(\theta)\left[\frac{\mu}{\gamma \cos H}\right] \tag{3}$$

$$S^*(\theta) = S(\theta)\left[\frac{\mu}{\gamma \cos H}\right]^{1/2} \tag{4}$$

where

$D^*(\theta)$ = intrinsic diffusivity (m)

$D(\theta)$ = liquid diffusivity ($m^2\ s^{-1}$)

μ = liquid dynamic viscosity ($N\ s\ m^{-2}$)

γ = liquid surface tension ($N\ m^{-1}$)

$S^*(\theta)$ = intrinsic sorptivity ($m^{1/2}$)

$S(\theta)$ = liquid sorptivity ($m\ s^{-1/2}$)

D^*, D, S^* and S are functions of the soil volumetric water content, θ.

Philip (1957) described D^* and S^* as properties of the porous medium, independent of the properties of the absorbing liquid. DeBano (1969a) and Hammond and Yuan (1969) applied equations (3) and (4) respectively to water and ethanol. They assumed that ethanol wet the soil with $H = 0^\circ$ ($\cos H = 1.0$) (Letey *et al.* 1962a), which enabled calculation of H for water infiltration.

DeBano (1969a) found that H values measured by the intrinsic diffusivity technique were

similar to those measured by capillary rise (Letey *et al.* 1962a) for a repellent soil. He stated that the diffusivity technique had advantages over other methods for H measurement because the diffusivity and therefore H values are linked to specific values of soil water content. Bahrani *et al.* (1973) also used equation (4) to calculate H and asserted that the technique had advantages over the capillary rise and direct observation methods because soil treatment to create wettability (e.g. by ignition, Emerson and Bond 1963) was unnecessary and the 'reaction time' (Zisman 1964) for solid-liquid contact was 30-60 minutes compared to 24 hours with Letey *et al.*'s (1962a) technique.

Despite potential advantages, researchers have found that H calculation from equations (3) and (4) may be erroneous. DeBano (1969a) found a discrepancy between the H values of a nonrepellent soil measured by intrinsic diffusivity and capillary rise which he could only explain as measurement errors. In contrast Hammond and Yuan (1969) found that the values of H calculated from intrinsic sorptivity were in good agreement to those measured by the capillary rise technique of Emerson and Bond (1963). Kijne (1967) used the capillary rise method of Letey *et al.* (1962a) to calculate H. He then applied equations (3) and (4) and found that neither D^* nor S^* were constant for a range of infiltrating solutions. Mustafa *et al.* (1970) found that equations (3) and (4) adequately described infiltration of water and organic liquids into glass beads and nonrepellent soil. The equations also held for infiltration of organic liquids into repellent soil, but not for water into a repellent soil.

Philip (1969) corrected his earlier work. He pointed out that D^* and S^* depend upon H in a very complex way so that the inclusion of H in equations (3) and (4) was unjustified. He therefore redefined D^* and S^* as equations (5) and (6) respectively:

$$D^*(\theta) = D(\theta)\left[\frac{\mu}{\gamma}\right] \qquad (5)$$

$$S^*(\theta) = S(\theta)\left[\frac{\mu}{\gamma}\right]^{1/2} \qquad (6)$$

Philip (1971) quoted Farrell's (1963) criticism that 'the contact angle can only be

dissociated from the geometry of the soil if the porous medium conforms to (an) idealised capillary tube model. For any porous medium in which the walls of the pore channels diverge and converge, a unique relationship between the relative sorptivity and contact angle does not exist'. Philip (1971) went on to point out that even for circular-cylindrical pores, scaling is exact only in the limit where pore diameter is negligibly small compared with pore length, therefore observations on porous media such as soils yield, at best, *apparent* contact angles which cannot be related directly to the contact angle at interfaces within the medium.

Bond and Hammond (1970) used scanning electron micrographs of water drops lying upon sand grains to explore the relationship between the *real* contact angle of individual grains and the *apparent* contact angle measured when water drops were placed between sand particles. They found that the *apparent* contact angle was equal to the *real* contact angle plus the angle of pore divergence. Surface roughness of the sand grains did not explain the differences between measured values of *real* and *apparent* contact angle.

For the reasons outlined by Philip (1971), measurement of an apparent contact angle to quantify repellency is inappropriate and misleading. Tillman *et al.* (1989) have developed an index based upon the intrinsic sorptivity of the soil medium as defined in equation (6) which involves calculation of a dimensionless 'repellency index' (RI).

B. Repellency Index (RI)

The RI is based upon the theory of intrinsic sorptivity described above and was seen to offer two major advantages over other techniques for repellency measurement (Tillman *et al.* 1989). Firstly, sorptivity is a well-defined soil parameter with physical significance. Secondly, sorptivity may be rapidly measured in the laboratory or *in situ* in the field. Furthermore, compared to contact angle measurements, sorptivity measurements using permeameters are relatively straightforward (Clothier and White 1981; Perroux and White 1988). Tillman *et al.* (1989) measured infiltration of water and 95% ethanol at a -0.4 kPa supply potential which removed the effect of soil pores with diameter > 0.74 mm. Air entry into the apparatus *via* a hypodermic needle maintained a constant supply potential so

that a constant pore size range conducted liquid (fig. 1.6). Sorptivity to water, S_w and to ethanol, S_E was calculated and equation (6) applied, from which equation (7) was derived.

$$S_w = \left[\frac{(\mu_E/\gamma_E)^{1/2}}{(\mu_W/\gamma_W)^{1/2}}\right] S_E \quad (7)$$

where

μ_E = viscosity of ethanol at 20 °C (0.0012 N s m^{-2})

γ_E = surface tension of ethanol at 20 °C (0.023 N m^{-1})

μ_W = viscosity of water at 20 °C (0.0010 N s m^{-2})

γ_W = surface tension of water at 20 °C (0.073 N m^{-1})

Therefore, when values for the relevant parameters are inserted, in nonrepellent media:

$$S_W = 1.95\ S_E \quad (8)$$

So the RI was defined as

$$RI = 1.95\ \left(\frac{S_E}{S_W}\right) \quad (9)$$

such that in non-repellent media, RI = 1.0. Tillman *et al.* (1989) found that equation (9) held for initially dry, acid-washed sand, as expected (i.e. RI = 1.0). However, they found that when the acid-washed sand was initially moist S_E remained unchanged but S_W was reduced, giving RI values > 1.0 but < 1.95. They postulated that in a nonrepellent soil, regardless of initial water content $S_E < S_W$, so that RI < 1.95.

Tillman *et al.* (1989) measured the RI of a moist sandy loam which appeared to absorb water 'normally'. They found RI was 140 during the first 30 s of water infiltration but declined to approximately 7 as time increased due to increased water sorption. Increased water infiltration rate with time in repellent soil has been reported by De Bano (1969c), and may be due to adsorption of vapour water molecules (Malik *et al.* 1981; DeBano 1969a).

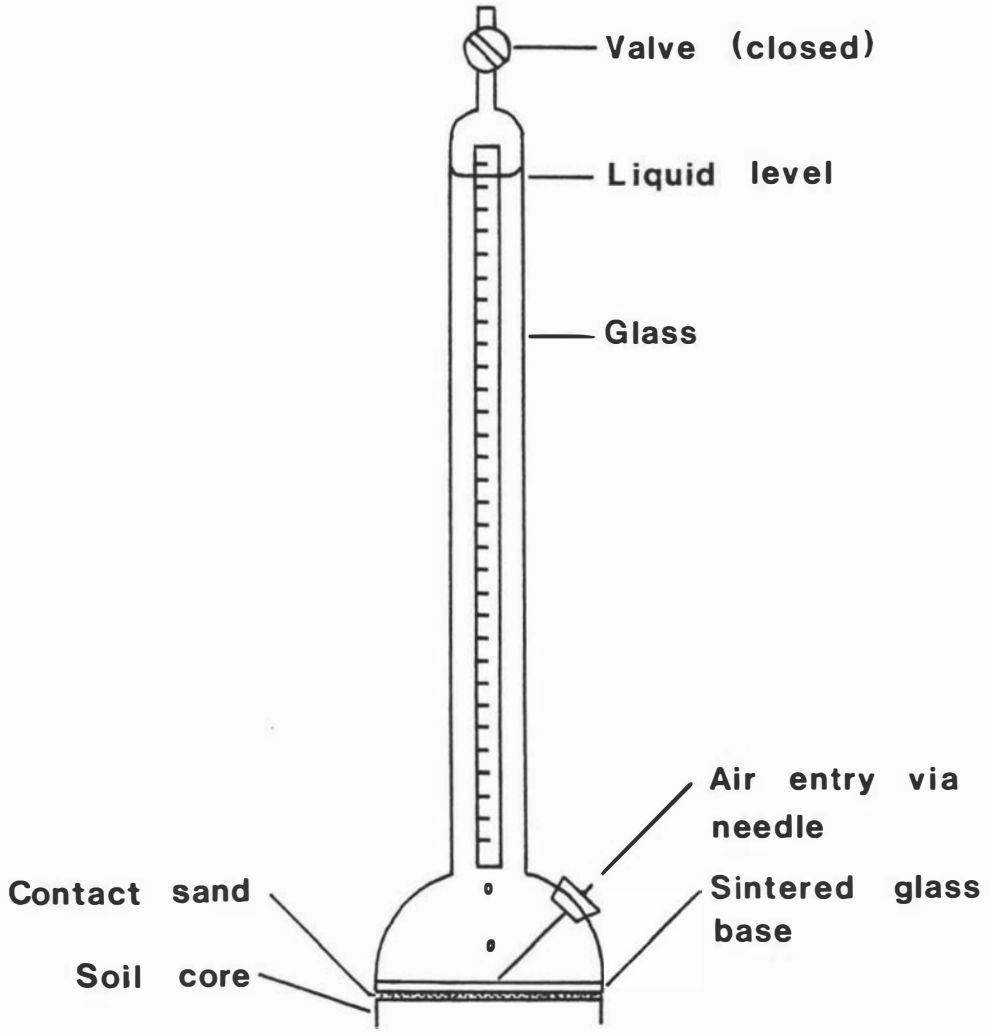


Figure 1.6. The disc permeameter used to measure water and ethanol sorptivity in undisturbed soil cores for calculation of the intrinsic sorptivity 'Repellency Index'.

Wallis *et al.* (1991) evaluated the RI index on a wide range of New Zealand soils and compared the index with the WDPT and MED techniques. They found that the RI measured all soils repellent (RI > 1.95) at field moisture conditions, and was more sensitive than the WDPT or MED tests and therefore particularly useful for evaluating soils with low degrees of repellency. A further advantage of the RI is that it is a physically significant parameter which can be used to calculate actual and 'potential' short-time water infiltration which may then be compared with rainfall and irrigation intensities. Wallis *et al.* (1991) undertook such comparisons and found that repellency was hydrologically significant, even in soils which appeared to wet normally. The RI may be measured *in-situ* or on undisturbed cores at either field-moist or air-dry conditions. Elimination of macropore flow using a negative supply potential reduces the effect of disturbance when cores are used.

C. Infiltration

Measurement of water infiltration rates have been used to indicate the severity of repellency since the earliest studies of the problem. Letey *et al.* (1962c) excavated basins to measure *in situ* infiltration under ponded conditions. Ring infiltrometers have also been used widely to measure *in situ* infiltration (Bond 1964; Wilkinson and Miller 1978; Taylor and Blake 1982; King 1981; McGhie and Tipping 1984; Wallis *et al.* 1990a). Other authors have used a range of rainfall simulation devices to measure *in situ* infiltration, runoff and erosion rates (Krammes and Hellmers 1963; Gilmour 1968; Hussain *et al.* 1969; Meeuwig 1971; McGhie and Tipping 1984). Laboratory infiltration studies have been used with either undisturbed soil cores (Wilkinson and Miller 1978) or repacked soil columns (Pelishek *et al.* 1962; Morgan *et al.* 1966; Mustafa and Letey 1970; Miyamoto 1985).

King (1981) compared the results of a small ring infiltrometer (SRI) test with measurement of the apparent contact angle, H by capillary rise (Emerson and Bond 1963) on 101 sandy soils from South Australia. He found that the relationship between $\log_{10}$SRI and H was nearly linear for $H > 81^\circ$, but was curvilinear when the whole range $60^\circ < H < 101^\circ$ was examined. The variability in the relationship between $\log_{10}$SRI and H

increased when $H > 92^{\circ}$, which King proposed was due to water being forced between the soil and the walls of the infiltrometer ring in the SRI test and the capillary tube in the contact angle test. Despite the efforts of King (1981) to define a relationship between infiltration rate and more precise measurements of repellency, infiltration measurements generally only provide information regarding the effect of repellency when compared with measures of the same, nonrepellent soil. They may be used to compare untreated and wetting-agent treated soil (e.g. McGhie and Tipping 1984) or to compare soil at different proximate locations, such as within a golf green (Wilkinson and Miller 1978) or within a soil type (Wallis *et al.* 1990a).

Indirect 'measurements' of infiltration may be used to determine the effect of repellency. Osborn *et al.* (1967) inferred the effect of repellency upon infiltration by measuring germination and establishment of seeds placed on untreated and wetting-agent treated repellent and nonrepellent soil in pots at 0° or 30° slope. They found a large effect of repellency upon the germination and establishment of seeds sown on the slope, but not upon those sown on level soil. Wallis *et al.* (1990b) improved the technique of Osborn *et al.* (1967) by sowing seed below the soil surface, and were able to measure the effect of repellency upon seedling emergence in level trays of soil.

Fink and Myers (1969) and Fink (1970) measured the 'infiltration resistance' of repellent soil by measuring the applied pressure necessary to initiate water flow into the pore structure. The breakthrough pressure data for sands treated with increasing quantities of synthetic repellent chemicals provided identical information to the contact angle data which was directly measured from a large water drop on the soil surface. Fink and Myers (1969) noted that the breakthrough pressure method was more difficult and time-consuming than the contact angle technique. Consequently, the breakthrough pressure technique has not been used in other studies.

Infiltration into repellent soil produces a high spatial variability of soil water content over small distances (section IV.G). Sawada *et al.* (1989) have developed the 'SOWADIN' index to measure the distribution of water in sections of soil following infiltration with and without applications of wetting agents. The SOWADIN index uses computer-assisted tomography applied to gamma-ray attenuation measurements and is therefore not widely

applicable outside research institutions which have the appropriate equipment.

D. Water Drop Penetration Time (WDPT)

The WDPT method simply consists of placing a water drop on the soil surface and recording the time taken for the water to penetrate the sample (Letey 1969). Normally, soil samples are first sieved, placed upon a dish and the soil surface smoothed by hand to provide standard conditions, since surface roughness and pore geometry affect WDPT (Wessel 1988). Richardson and Hole (1978) modified the WDPT test by using 2 ml of water instead of a single drop. They asserted that this improved repeatability and increased the ease of observation. Fink (1970) compared the height of c. 30 mm diameter water drops resting upon soil with that of a similar drop resting upon a smooth, nonporous solid surface with a 90° apparent contact angle to produce a 'relative repellency' measure. Neither of the modified techniques have been widely used and many authors have simply increased replication to improve estimates of WDPT.

There have been a number of developments in the interpretation of the WDPT test. Letey (1969) considered that the WDPT divides soils into two broad categories; those with apparent contact angles, H above and those below 90°. If the water drop forms a ball on the soil surface, $H > 90°$, and the soil is considered repellent. Watson and Letey (1970) pointed out that water will only penetrate a porous medium once $H < 90°$. Normally the water drop will eventually penetrate the soil, indicating that H must decrease over time (Letey 1969). Therefore the method may be a better index of repellency persistence than an actual estimate of the initial contact angle (Letey 1969; Watson and Letey 1970).

The apparent decline of H over time may be explained by the occurrence of a solid-liquid interaction (John 1978) which may involve adsorption of vapour water molecules (Malik *et al.* 1981). DeBano (1969a) monitored temperature fluctuations at the wetting front of repellent and nonrepellent soil which indicated that vapour mechanisms of water movement were more important in the repellent soil.

A number of authors have attempted to correlate WDPT with measurements of H. Watson

and Letey (1970) found that the WDPT method ranked a range of natural and synthetic repellent soils in the same order of repellency severity as the capillary rise method of Letey *et al.* (1962a) for H measurement. Scholl (1975), King (1981) and Wessel (1988) have reported significant linear relationships between the logarithm of WDPT and H. In contrast Richardson and Hole (1978) and McGhie and Posner (1981) have recorded a poor relationship between WDPT and H (measured by the techniques of Letey *et al.* (1962a) and Emerson and Bond (1963) respectively). The study of McGhie and Posner (1981) was an 'unnatural' situation, comprising nonrepellent soil amended with ground plant material, compared to the other studies which utilised a range of repellent soils.

The reported relationships between WDPT and H have been markedly dissimilar. Scholl (1975) used Letey *et al.*'s (1962a) technique to measure H and correlated $H = 90^\circ$ with WDPT c. 10 000 s. King (1981) used Emerson and Bond's (1963) technique for H measurement and correlated $H = 90^\circ$ with WDPT = 260 s. Wessel (1988) directly measured H and correlated $H = 90^\circ$ with WDPT < 1 s. The differences in the correlations may be due to the different techniques for H measurement employed which have widely different 'reaction times' for solid-liquid contact. However the correlation differences tend to substantiate the perceptions of Letey (1969) and Watson and Letey (1970) that the WDPT is a better measure of repellency persistence than of initial resistance to wetting.

As a consequence, the distinction between 'repellent' and 'nonrepellent' soils based upon WDPT is arbitrary. Watson and Letey (1970), John (1978) and Miller and Letey (1975) chose WDPT = 5 s as the division; Richardson and Hole (1978) used 8 s; Savage *et al.* (1972) used 1 s. In some cases further classification of repellency severity has also been made. For example, Roberts and Carbon (1972) assigned WDPT > 300 s to soils with $H > 90^\circ$, WDPT 1-300 s with H c. 70-90° and WDPT < 1 s with $H < 70^\circ$.

The WDPT method is only capable of measuring a narrow range of repellency within a few degrees span of $H = 90^\circ$ (King 1981). He found that WDPT < 1 s for $H < 75^\circ$, which indicates the limitations of the technique for quantifying low degrees of repellency. WDPT > 1 h have been measured (Savage *et al.* 1972; Roberts and Carbon 1972; Singer and Ugolini 1976; Wallis *et al.* 1990a), which indicates the limitation of the technique for

quantifying severe repellency.

The WDPT method may also have limited application for very coarse mediums. Richardson and Hole (1978) measured a low WDPT on a coarse sand with a high *H* value. Hillel and Berliner (1974) found that infiltration may be enhanced through a system of large repellent aggregates which allow rapid macropore flow and reduce aggregate sorption. On the other hand, in some studies WDPT has proven more useful than measurements of *H*. Richardson and Hole (1978) measured a very high WDPT of a litter layer which had a low *H*, which may indicate that the capillary rise technique is not suitable for repellency measurements of such material.

Although the WDPT method has the several limitations described, it is simple and rapid, and has therefore been used in many studies. King (1981) reported that 200 samples may be tested per person-day. Furthermore, the technique is suited to measurements *in situ* or on undisturbed samples. Giovannini and Lucchesi (1984) measured *in situ* WDPT = 800 - 900 s and undisturbed soil WDPT = 700 - 760 s of an Italian forest soil. *In situ* WDPT measurements have also been used in turf evaluation (Wilkinson and Miller 1978; Charters 1980; Templeton and Rodriguez 1988) and a large-scale survey (DeByle 1973). The simplicity of the WDPT method enables its use by farmers and turf managers to identify and broadly characterise a repellent soil condition.

E. Ninety Degree Surface Tension (NDST)

The liquid-solid contact angle, *H* depends upon both the nature of the solid and the surface tension of the liquid, as defined in equation (1). Zisman (1964) reported a linear relationship between cos *H* of plane surfaces and the surface tension of an homologous series. He found that the highest surface tension at which there was complete wetting (i.e. $H = 0^{\circ}$) was more or less characteristic of the solid surface itself. He called this value the 'critical surface tension'.

Letey (1969) suggested that the critical surface tension may be developed as an index of repellency which could be used to determine optimum surfactant concentration for soil

application. Watson and Letey (1970) found that the linear relationship between cos H and liquid surface tension of Zisman (1964) held adequately for porous media. They developed the 'Ninety Degree Surface Tension' (NDST) method in which the surface tension at cos $H = 0$ ($H = 90°$) of soil samples was determined. The method consisted of preparing a series of aqueous ethanol solutions with varying surface tension, and finding the surface tension at which a drop will remain on the soil for an arbitrary time period of 5 s. Watson and Letey noted that this method had application for determining the optimum dilution rate for surfactant addition to soil.

Miyamoto and Letey (1971) used a similar procedure to that of Watson and Letey (1970) to measure the NDST except that a range of pure liquids were used. This appeared to be a backward step, since a similar range of liquids were evaluated by Watson and Letey (1970) and produced a lower correlation coefficient between cos H and the liquid surface tension than the aqueous ethanol series. Furthermore, the aqueous ethanol series is less expensive, readily obtained and nontoxic (Watson and Letey 1970). Miyamoto and Letey (1971) discussed the use of liquids with a higher surface tension than water for NDST evaluation of 'wettable' soils. They pointed out that such liquids were rare and expensive, so that the NDST technique was best for repellent materials but not for extremely wettable materials.

Letey *et al.* (1975) divided the WDPT by NDST to derive the 'water repellency index' (WRI). WRI < 0.1 was categorised as a wettable soil; WRI from 0.1 to 1.0 slightly repellent; WRI from 1.0 to 10 moderately repellent; and WRI > 10 very repellent. John (1978) used the NDST and WDPT methods and calculated WRI for a range of New Zealand soils. He found that the NDST method was rapid, simple and sensitive for indicating the initial repellency of a soil, and in conjunction with WDPT (a measure of repellency persistence) could provide a good indication of the repellent qualities of a soil. However, he found that the relationship between NDST and WDPT was complex. For WDPT < 90 s the relationship was approximately exponential. For WDPT > 90 s there was no apparent relationship with NDST. As a consequence, the WRI index has not been widely used, although the WDPT and a modified NDST method (MED) have been applied in many studies.

F. Molarity of an Ethanol Droplet (MED)

The MED test was developed by King (1981) from the NDST test of Watson and Letey (1970). The MED test measures the molarity of an aqueous ethanol droplet required for soil infiltration within 10 seconds. The ethanol lowers the liquid-solid contact angle, increasing the rate of infiltration into repellent soil.

King (1981) compared the MED test with measurement of the apparent contact angle, H (Emerson and Bond 1963), WDPT and infiltration measured with a small ring infiltrometer (SRI). MED was highly correlated with H ($R^2 = 0.75$), however variability in the relationship increased in soil with measured $H > 92^\circ$ (MED > 2.0). King proposed that this was due to water being forced between the soil and the walls of the capillary tube in the contact angle test. King found that the MED test was not useful for media with low degrees of repellency, since MED = O when $H \leq 81^\circ$. For such soils King noted that the WDPT test can be treated as an extension of the MED test below MED = 0, however he found that WDPT declined to < 1 s when $H < 75^\circ$. The $\log_{10}$ WDPT data was correlated with H by a quadratic relationship ($R^2 = 0.85$).

The most important advantages of the MED test are its simplicity and rapidity, especially for severely repellent soil which may have WDPT in excess of one hour (Wallis *et al.* 1991). The major disadvantage of the test is that it is unsuitable for soils with a low degree of repellency.

G. Thermal Analysis

In a discussion of measurement techniques at the U.C., Riverside conference on repellent soils, the possibility of using the heat of wetting to indicate the level of free energy associated with the solid matrix was discussed (Hammond and Yuan 1969). This possibility was not explored until the Russians Lishtvan and Zuyev (1983) measured the heat of wetting to characterise the affinity of peats for water. Mallik and Rahman (1985) found that repellent soil thermally released water more easily than nonrepellent soil. Measures of thermal release were generally well correlated with WDPT and direct

measures of *H*. Differences between thermal release, WDPT and *H* were ascribed to the fact that WDPT and *H* measure the interaction of water with the solid surface whereas thermal release is a measure of both surface and bulk properties of the soil. Application of thermal analysis for repellency measurement is likely to be limited because it demands specialised equipment and it only provides semi-quantitative data. Further evaluation of thermal analysis is necessary to compare its relative merits with other techniques on a range of soils.

IV. DEVELOPMENT OF REPELLENCY

A. An organic coating on soil particles

Although numerous researchers have attempted to determine the causes of repellency, research findings have not been entirely conclusive, and would suggest that there are a number of causes which are site-specific. However, a number of mechanisms appear common to most soils which are important to understand. Fundamentally, most workers agree that a coating of organic matter on the surface of soil particles imparts repellency (Bond 1969a).
Studies employing high magnification of repellent sand grains have shown the presence of an organic coating which was not present on sand grains from nonrepellent soil (Wilkinson and Miller 1978; Rankin and Ross 1982)(fig. 1.7a,b).

Bozer *et al.*(1969) found that synthetic materials which decreased soil wettability included many organic compounds with amphiphilic characteristics (with both hydrophilic and hydrophobic groups). They postulated that the hydrophilic end adsorbs to the hydrophilic soil surface, probably by complex formation, by hydrogen bonding and/or adsorption by Van der Waal's dipole-dipole interaction. The hydrophobic portion of the chemical would then effectively create the 'new surface' of the soil particle.

Ma'shum and Farmer (1985) produced evidence which indicated that the molecular orientation of organic matter determines repellency of the soil. They found that prolonged shaking of repellent soil detached organic matter coatings from sand particles and reduced

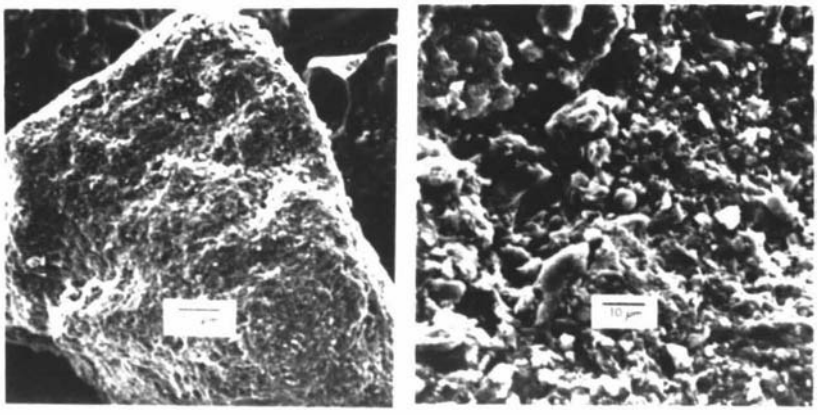


Figure 7A. Scanning electron micrographs of 'clean' sand grains from a nonrepellent golf green site, with a general absence of an organic coating.

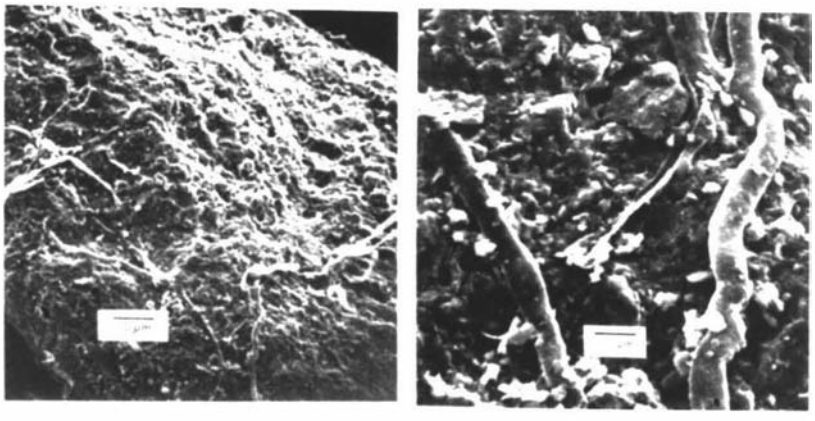


Figure 7B. Scanning electron micrographs of sand particles from a repellent golf green site, with an organic coating and tubular strands of fungal hyphae. After Rankin and Ross (1982).

repellency. Wallis *et al.* (1990a) made similar observations (section V.A).

There is conflicting evidence regarding the thickness of the repellent coating necessary to induce maximum repellency. Fink (1970) found that repellency increased rapidly with increasing addition of synthetic repellent chemicals to a nonrepellent sand, until a point was reached when repellency of the soil did not increase. He assumed that at this point complete, 'monolayer' coverage of the sand particle surfaces was achieved. Nakaya *et al.* (1977b) made similar observations when humic acid was added at increasing concentration to a nonrepellent sand. In contrast, Ma'shum *et al.* (1988) found that 16 times the amount of cetyl alcohol necessary for monolayer-coverage was necessary before maximum repellency developed. They suggested that the 'excess' cetyl alcohol may have been necessary to coat applied water as well as the sand grains.

A surprisingly small amount of organic matter is necessary to produce severe repellency. Bond and Harris (1964) found that Australian sands with $< 0.1\%$ total organic carbon had apparent contact angles, H (Emerson and Bond 1963) greater than 90°. De Bano *et al.* (1970) reported $H = 85^\circ$ in sands with 0.02% organic matter. DeBano (1969a) pointed out that the total organic matter content bears no relation to the degree of repellency since some sands with > 5 %C were more easily wetted than others with 0.1 %C. Savage *et al.* (1969b) found that the two most severely repellent sands innoculated with fungal cultures had the lowest organic matter content. They suggested that an inverse relationship existed between organic matter content and repellency, which was difficult to substantiate upon the basis of so few observations. Singer and Ugolini (1976) attempted to correlate the repellency of a number of soil and litter horizons with %C, however there was a large amount of variation about the regression line (WDPT ranged from 0.2 s to $>$ 100 s at 2 %C). It would appear that the nature rather than the quantity of soil organic matter is the most important determinant of repellency severity.

However within a soil profile the severity of repellency is related to the quantity of organic matter present. Scholl (1975) and Singer and Ugolini (1976) reported a decrease in repellency with depth which was closely associated with decreasing organic matter. Wallis *et al.* (1990a) reported a strong correlation ($R^2 = 0.79$) between %C and the MED index with depth in a sandy soil under pasture.

The thickness of the repellent layer in a soil appears to be site-specific, however some generalisations may be made. DeBano and Rice (1973) stated that repellency usually occurs within 100 - 150 mm from the soil surface, which was supported by observations of DeByle (1973), Reeder and Jurgensen (1979) and Wallis *et al.* (1990a). However in burned soils the repellent layer may be only 10 - 20 mm thick and at any depth within the topsoil (section IV.F). In sports turf the repellent layer may be restricted to 20 - 50 mm (Wilkinson and Miller 1978; Tucker *et al.* 1990), however Wallis *et al.* (1989b) found that soil from New Zealand golf courses was repellent to an average depth of 100 mm. Singer and Ugolini (1976) found that repellency extended to > 300 mm in some forested soils.

Generally the more extreme cases of repellency are found in sandy soils. Sand grains are more readily coated by organic material due to their relatively low specific surface area (McGhie 1987). In an analysis of heat-induced repellency, DeBano *et al.* (1970) found that the thickness of the repellent layer increased as percent silt and clay decreased. The thickest and most intensely repellent layer was produced in a uniform sand of particle diameter < 425 μm. The effect of texture upon repellency was attributed to the large differences in specific surfaces of the soils, which ranged from 7.7×10^{-3} to 55 $m^2 g^{-1}$.

In sports turf, widespread repellency may be related to the use of sand as a medium. Rieke (1981) pointed out that with the increased emphasis upon high sand content soil mixes in the construction of new greens and the widespread acceptance of sand topdressing on old greens, the potential for repellency development will increase.

Studies of repellency were mainly restricted to sandy soils for many years, however repellency is not restricted to sands. Bond (1969a,b) noted that small repellent pockets were found in Western Australian loams which contained up to 20% clay. Giovannini *et al.* (1983) reported severe repellency in heavy textured Italian soils (40% clay) and McGhie and Posner (1980) reported severe repellency in Australian soils with >20% clay. McGhie and Posner proposed that clay aggregates had become coated with hydrophobic material; a mechanism which Wallis *et al.* (1991) supported in research with a New Zealand humic clay.

1. Peat

Despite general recognition of the problem of repellency in peats there have been surprisingly few studies and consequently the mechanism of repellency development in peats is poorly understood. Van't Woudt (1959) first reported repellency of peat bogs in New Zealand and later explained (van't Woudt 1969) that when peats are drained the surface layers may undergo irreversible drying. Lishtvan and Zuyev (1983) reported that peat water absorption was reduced when dried beyond a certain limit (typically below 0.30 g/g). They argued that changes in the peat pore system rather than the development of repellency were responsible for this change, however they reported that dry peats could be readily wetted with organic liquids of low surface tension which indicated that repellency had developed. Nakaya *et al.* (1977a) measured severe repellency (WDPT > 300 s) of a dry Japanese peat soil.

The nature of the repellency mechanism may differ between peat and other soils due to the ways in which water is held in peats (Lishtvan and Zuyev 1983). Flaig (1986) pointed out that the physical nature of peat differs fundamentally from that of soil, primarily as a result of the anaerobic conditions under which humification of peat-forming plants occurs. In peat, the decomposition products of plant constituents such as lignins and the mechanical structure of mosses and graminaceous plants yield macroporous, spongelike products which absorb large quantities of water very strongly (Kwak *et al.* 1986). However it has been suggested (Kwak *et al.* 1986) that peat surfaces are predominantly hydrophobic, resulting in restricted infiltration when the peat dries.

Peat development and composition may affect the affinity of peat for water. Kay and Goit (1977) found that the most decomposed sphagnum moss peats had the highest water adsorption which they assigned to increased specific surface area and changes in organic matter composition. Flaig (1986) pointed out that chemical alteration during decomposition, especially of the lignins, makes the organic surfaces less repellent, which may at least partly account for Kay and Goit's (1977) observation. Lishtvan and Zuyev (1983) found that the water-affinity of a number of Russian peats developed from sedges changed insignificantly during mineralisation. The contrasting results with those of Kay and Goit (1977) may be due to the different plant origins of the peat bogs (section

IV.B.1).

Van't Woudt (1969) stated that repellent surface peat layers necessitated removal of the layer until a moist layer is exposed. However he pointed out that such management was unsustainable since the peat surface is gradually lowered and productivity decreased. Water table management or irrigation could be used to prevent excessive drying of the surface peat layers. Lishtvan and Zuyev (1983) reported that they had used wetting agents to improve peat wettability (section V.C).

2. Thatch

In sports turf, thatch may be a contributing factor to the development of repellent soil (Waddington 1969). Thatch is the layer of partially decomposed organic material which comprises the uppermost layer of most turf profiles, and is widely believed by turf managers to be responsible for the development of repellency in turf (commonly called 'dry patch' because of its 'patchy' occurrence). Thatch is known to reduce infiltration into turf when dry (Taylor and Blake 1982). However thatch is not a prerequisite for dry patch development (Danneberger and White 1988). Wilkinson and Miller (1978) found that thatch removal from dry patch cores did not significantly increase water infiltration. Irrigation water penetrated the turf and thatch but would not penetrate the thatch/soil interface. They concluded that repellency extended into the soil and was not merely a function of the thatch layer. Wallis *et al.* (1989b) found that although samples of thatch were severely repellent (MED 2.6 - 5.0), the soil-alone from 31 New Zealand golf greens was also severely repellent (MED 3.3 - 3.5).

Thatch control by a variety of mechanical means is an integral part of turf management, and would be expected to reduce the severity of repellency. However thatch control alone will not prevent the development and expression of repellency in turf. Techniques to ameliorate 'dry patch' in sports turf are discussed in section V.

B. Origin of the organic coating

1. Vegetation

The relationship between repellency and the principle origin of the organic coating, the vegetation cover, has occupied scientists since the studies of Jamison (1942, 1945) on citrus groves in Florida. Bornemisza (1964) added citrus leaves (*Citrus* sp.) to a nonrepellent sand and found that repellency was produced. The technique of Bornemisza (1964) has also been used by Roberts and Carbon (1972), McGhie and Posner (1980, 1981) and Reeder and Jurgensen (1979). Conclusions which may be drawn from these studies are limited because the plant material had not undergone natural decomposition and incorporation into the soil and the contribution of plant roots to soil organic matter was neglected. Studies other than those listed above have been based upon field surveys. One limitation of field studies is that they may not account for the contribution of past vegetation types to repellency development. Table 1.1 summarises studies which have examined the relationship between plants and repellency.

In general deciduous tree species have not been associated with repellency (the larch, a deciduous conifer, is an exception). Fire was a compounding factor in the study by Reeder and Jurgensen (1979) (section IV.F). Most coniferous plants, in particular *Pinus* species, have been associated with repellency development. However not all *Pinus* species impart repellency, therefore the likely effect of a species cannot be readily estimated from existing studies, even from plants within the same genus. Comparison of the existing studies is difficult because most have used relative measures of repellency such as *in situ* infiltration.

A large range of *Eucalyptus* species have been found to be associated with repellency in Australian field and laboratory studies. McGhie and Posner (1980) found that the leaf drip from *E. astringens* did not induce repellency in a nonrepellent sand, whereas comminuted litter induced severe repellency. Jamison (1942) had suggested that repellency under citrus trees was related to leaf drip, but later suggested that colloidal organic matter might be more important (Jamison 1945).

McGhie and Posner (1981) evaluated the effect of three cereal crops upon repellency.

Table 1.1. A summary of studies which have investigated the relationship between soil water repellency and vegetation species.

Vegetation Type	Associated or (Not Associated) with Water Repellency
Citrus spp.	Jamison 1942,1945; Wander 1949
Deciduous Trees	
Acer saccharum (Maple)	(Richardson & Hole 1978)
Quercus sp. (Oak)	(Richardson & Hole 1978) (Reeder & Jurgensen 1979)
Carya sp. (Hickory)	(Richardson & Hole 1978) (Reeder & Jurgensen 1979)
Populus tremuloides (Quaking aspen)	Reeder & Jurgensen 1979
Heath plants and Conifers	
Heath - unspecified - primarily *Calluna vulgaris*	van't Woudt 1959 Mallik & Rahman 1985
Vaccinium sp. and other *Erica* species	Richardson & Hole 1978
Tsuga canadensis (Hemlock)	Richardson & Hole 1978
Pinus resinosa (Red pine)	Richardson & Hole 1978 Reeder & Jurgensen 1979
Pinus sp. (Unidentified)	Richardson 1984
Pinus pinaster	Giovannini & Lucchesi 1984
Pinus monophylla	Holzhey 1969
Pinus jeffreyii (Jeffrey pine)	Hussain *et al.* 1969
Pinus radiata (Radiata pine)	(Bond 1964)
Pinus strobus (White pine)	(Reeder & Jurgensen 1979)
Pinus banksiana (Jack pine)	Reeder & Jurgensen 1979
Juniperus spp.	Holzhey 1969
Juniperus osteosperma	Scholl 1971
Larix occidentalis (Western larch)*	DeByle 1973
Pseudotsuga menziesii (Douglas fir)	DeByle 1973
Picea engelmanii (Engelman spruce)	DeByle 1973
Eucalypts	
Eucalyptus spp.	Gilmour 1968; Bond 1964 McGhie & Posner 1981
E. marginata (Jarrah)	Roberts and Carbon 1972
E. astringens (Brown mallet)	McGhie & Posner 1980, 1981
Cereal Crops	
Triticum aestivum (Wheat)	(McGhie & Posner 1981)
A. sativa (Oats)	(McGhie & Posner 1981)

Vegetation Type	Associated or (Not Associated) with Water Repellency
H. vulgare (Barley)	McGhie & Posner 1981
Legumes	
Medicago sativa (Lucerne)	Bond 1964; Roberts & Carbon 1972; (McGhie & Posner 1981)
Lupinus cosentinii (W.A. blue lupin)	(McGhie & Posner 1981)
Trifolium subterraneum (Subterranean clover)	Roberts & Carbon 1972 McGhie & Posner 1981
Grasses	
Phalaris sp.	Bond 1964
E. calcycina (Perennial veldt grass)	McGhie & Posner 1981
Agrostis spp. (Bentgrasses)	Wilkinson & Miller 1978
S. secundatum (Buffalo grass)	McGhie & Posner 1981 (McGhie & Posner 1981)
Cynodon sp. (Couch grass)	(McGhie & Posner 1981)
Desert scrub	
Larrea divaricata	Adams *et al.* 1969
Prosopis juliflora	Adams *et al.* 1969
Cercidium floridum	Adams *et al.* 1969

Deciduous conifer.

Study of plant rotation systems showed that repellency increased under subterranean clover pasture but was reduced under wheat. They suggested that in suitable farming systems, crops such as wheat could be grown to reduce repellency, however they demonstrated that the change to wheat would need to be made before severe repellency developed.

Leguminous species have been found to differ in their effect upon repellency. The contrasting findings of Bond (1964), Roberts and Carbon (1972) and McGhie and Posner (1981) with lucerne may be due to differing experimental procedure. Bond (1964) measured field infiltration rates whereas McGhie and Posner (1981) added freshly ground plant top material to nonrepellent sand and Roberts and Carbon (1972) used a range of extractants and adjusted the pH of plant sap before addition to nonrepellent sand. For the reasons outlined previously, the field study of Bond (1964) would be the most reliable of the three studies.

The relationship between repellency and native or introduced grass species has been explored in natural, agricultural and turf ecosystems. Holzhey (1969a,b) found that grasses in the Southern Californian foothills developed a thin root zone with high organic matter content in which seasonal repellency was most persistent. Forbs usually did not develop such a zone, and were most often associated with shorter-lived seasonal repellency. In a study of water infiltration into a South Australian sand under a range of plant species Bond (1964) found that the soil under *Phalaris* sp. pasture was most severely repellent. Sites bare of vegetation were more dry and repellent than adjacent sites under annual grasses. The bare sites must have previously supported plants which contributed to the organic coating. Bond (1969a) reported that bare coastal and desert dune sands were nonrepellent, but became repellent after the establishment of semipermanent or permanent vegetation. Even dunes which had a sparse cover of sedges were found to be repellent.

In turf, 'dry patch' has been found to be prevalent on bentgrass greens (Wilkinson and Miller 1978). However this may be due to the relatively shallow-rooted nature of the species and subsequent poor drought tolerance, rather than the composition of the plant (Bolton 1990). McGhie and Posner (1981) found that ground tops of buffalo grass did not induce repellency in nonrepellent sand. However they measured severe repellency on ten

year old lawns of buffalo grass and couch. This was a further example of the superiority of field evaluation of the influence of vegetation upon repellency.

Adams *et al.* (1969) found a relationship between repellency and the establishment of annual plants in California desert scrub vegetation. They found that soil beneath burned *Larrea divaricata*, *Prosopis juliflora* and *Cercidium floridum* hummocks was repellent and supported none or few annual plants up to four years after fire.

2. Soil microorganisms

In 1917, Schantz and Piemeisel showed that fairy rings in pastures and crops were due to basidiomycete fungi and that the presence of basidiomycete mycelia was associated with poor soil water absorption. Bond and Harris (1964) found that repellent Australian sands always had a zone of copious fungal proliferation, with a regular occurrence of basidiomycete fungi. Some basidiomycete mycelia themselves had a wax-like, repellent surface. However, they noted that whether the basidiomycetes themselves were a major source of the repellent organic material remained uncertain, because many other hyphomycete fungi and bacteria were also found in the repellent soils.

Bornemisza (1964) found that mycelia of the fungus *Aspergillus niger* added to a nonrepellent fine sand induced repellency. In a similar experiment, Savage (1969b) innoculated sterile sand with cultures of a range of fungal spores. However, in contrast to Bornemisza he found that only *Pencillium nigricans* and *Aspergillus sydowi* caused mild repellency while *A. niger* and five other fungi did not develop measurable repellency in a 53-day incubation. Savage *et al.* (1972) found that heating a fungal sand culture prepared by the method of Savage *et al.* (1969b) produced repellent organic substances which were very similar to those responsible for repellency in a soil susceptible to heat-induced repellency (section IV.F).

McGhie and Posner (1981) found that the effect of fungi upon repellency varied as widely as the effect on repellency of the different plant species. They found that cultures of soil fungi added to a nonrepellent sand and mixtures of plant material could either increase or

decrease repellency, depending upon the relative repellency of the fungi and the plant. Bond (1964) also suggested that different degrees of repellency in soils under a range of plant species may be due to differing suites of microorganisms growing in association with the plants. Similarly, Richardson and Hole (1978) implicated fungal mycelia in the development of repellency under mor forest humus which were not prevalent under less repellent mull humus from deciduous forests. DeByle (1973) found that mor forest litter was extremely repellent one year after burning only if it contained fungal mycelia. However Roberts and Carbon (1972) found that repellency could be induced in a nonrepellent sand with the addition of microorganism cultures, with or without the presence of plant material.

The specific microorganism(s) involved with repellency development may vary between soils. Jex *et al.* (1985) found that the repellency of an incubated soil was most strongly correlated with the population of actinomycetes rather than with the number of fungi or bacteria. Scanning electron micrographs of the repellent sand grains also revealed high populations of actinomycetes.

The contribution of fungi in the development of repellency in sports turf has received some attention. Wilkinson and Miller (1978) undertook an extensive study of the causes of 'dry patch' in Ohio, U.S.A. sand golf greens. They found that the organic coatings on repellent sand grains appeared to incorporate fungal mycelia, but no difference was found between the fungal species composition of non-dry patch and dry patch soil. 'Fairy rings' are a common problem in turf produced by basidiomycete fungi which consist of a circle of lush turf growth, stimulated by nitrogen mineralisation produced by the radially extending fungal mycelia. Within the lush ring of growth is a dense mycelial 'zone of inhibition', where turf growth suffers (McIver 1988). Toxins, primarily hydrogen cyanide are released from the fungi (Lebeau and Hawn 1963) and the turf develops repellency (Wilkinson and Miller 1978) (fig. 1.8). Whitely and Baldwin (1990) found that, compared to unaffected soil, the zone of inhibition had lower soil water content and consequently higher soil strength which was likely to restrict root penetration.

It appears that although a direct contribution of soil microorganisms to the development of repellency may be shown in incubation studies, in the field they normally play a more

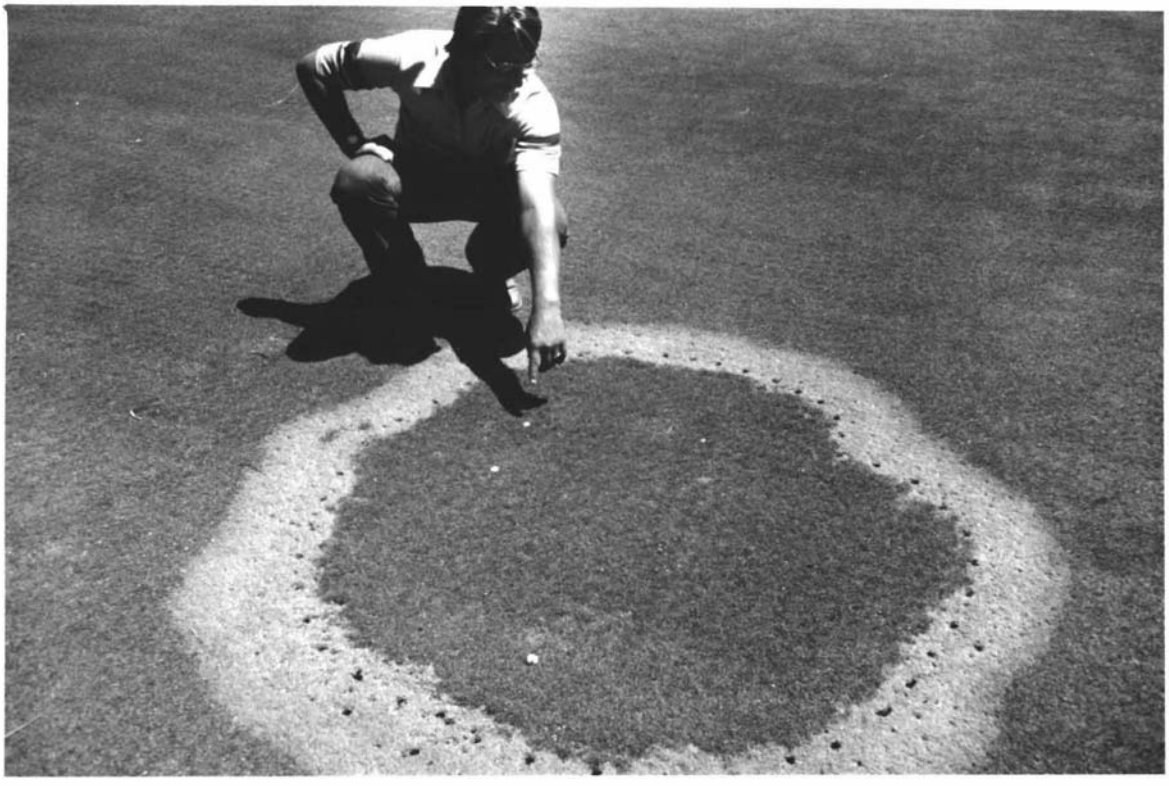


Figure 8. Water repellent turf ('dry patch') in the 'fairy ring' pattern characteristic of basidiomycete fungi. Note that soil cores have been removed from the dry patch ring. Also note that dry patch is most often found in irregular patterns (photo P. Rieke).

indirect role through organic matter decomposition and hence the accumulation of the organic coating on repellent soil particles. Soil microorganisms growing in association with certain plants may produce repellent decomposition products. When dense populations of a specific microorganism develop, such as in the case of basidiomycete fungi in 'fairy rings'(Schantz and Piemiesel 1917) or fungi in forest litter (DeByle 1973), the microorganism may directly affect the development of repellency.

C. Chemistry of the organic coating

Many extractants have been used in attempts to isolate and characterise the repellent organic coating. Methanol, ether, ethanol and benzene have had variable effectiveness which reflects different extraction conditions but may also indicate differences in the nature of the repellent coating of the soils studied (Jamison 1945; Wander 1949; Savage *et al.* 1969b; Ma'shum *et al.* 1985, 1988; Roberts and Carbon 1972; McGhie and Posner 1980; Giovannini *et al.* 1983; Jackson and Gillingham 1985). Other extractants such as acetone (Savage *et al.* 1969b; Roberts and Carbon 1972; McGhie and Posner 1980) and chloroform (McGhie and Posner 1980; Ma'shum *et al.* 1985) have been found consistently ineffective. Chloroform treatment actually increased repellency, which was ascribed to either molecular reorientation of repellent organic matter, e.g. alkyl chains, or redistribution of repellent material on exposed nonrepellent surfaces. Cold water has been found ineffective, however boiling hot water or stirring with heated water has been found to remove repellency (Roberts and Carbon 1972; McGhie and Posner 1980). The physical disturbance of boiling and stirring may have reduced repellency (Ma'shum and Farmer 1985; Wallis *et al.* 1990a).

Removal and identification of the organic matter fraction responsible for repellency is difficult. Although the 'effective' extractants described may render repellent soil nonrepellent, the extracted molecules may bear little resemblance to the molecules responsible for the hydrophobic layer surrounding soil particles due to possible cleavage of covalent linkages and changes in molecular conformation. Ma'shum *et al.* (1988) found that an amphiphilic mixture of *iso*-propanol and 15.7 M ammonia extracted organic materials responsible for repellency in a range of repellent Australian soils after 8 h under

soxhlet reflux conditions. After extraction the repellent soils measured MED = 0 and the extracted materials restored repellency of acid-washed or ignited sands to levels comparable to the original, repellent soils. Although Ma'shum *et al.* (1988) claimed that 'complete' extraction had been achieved, soils with MED = 0 may have hydrologically significant repellency as discussed in section III.B and shown by Wallis *et al.* (1991).

The nature of the organic coating on repellent soil particles has been the subject of much investigation and debate. Bozer *et al.* (1969) found that synthetic substituted phenols could induce repellency when added to nonrepellent sand. The position and nature of the substitution groups on the benzene ring determined the repellency characteristics of the compound. Chlorosilanes, amines and nitrogen-containing heterocyclics also exhibited repellency. Savage *et al.* (1969b) also found that amines induced repellency when added to a nonrepellent sand. The substituted phenols and other organic compounds identified by Bozer (1969) are naturally occurring compounds in soil, with phenolic compounds very common in natural resins. From infrared spectra of the extract from a repellent soil, Giovannini and Lucchesi (1984) hypothesised that an ester between phenolic acids and polysaccharide-like substances was responsible. However Roberts and Carbon (1972) found that an Australian sand remained repellent after a soxhlet extraction of resins with hot ethanol.

Savage *et al.* (1972) captured the volatilised products of a Californian soil susceptible to heat-induced repellency (section IV.F). Adsorption chromatography with a benzene-acetone solvent isolated three fractions which produced repellency when added to a nonrepellent sand. The elution pattern was as follows: fraction I, very pale yellow, 4 - 7.5% of extract; fraction II, dark brown, 14 - 39%; fraction III, dark brown, 7%. Giovannini and Lucchesi (1984) also obtained an elution pattern with three fractions following adsorption chromatography of a benzene extract: fraction I, pale yellow, 25%; fraction II, yellowish green, 25%; fraction III, pale brown, 40%. It would appear that there were some similarities in the organic matter fractions responsible for repellency in the two soils.

Ma'shum *et al.* (1988) used thin layer chromatography to identify three elution fractions of a benzene/ethanol (2:1 v/v) extract. However they did not describe the colour or

relative proportions of the fractions. An *iso*-propanol/ammonia extract produced only two fractions which occupied different positions on the chromatogram than the fractions of the benzene/ethanol extract. Savage *et al.* (1972) found that thin layer chromatographic analysis indicated that the three fractions did not comprise pure materials. Elemental, infrared and NMR analyses indicated that fraction I was a mixture of aliphatic hydrocarbons and fractions II and III were also aliphatic but contained up to 15% oxygen as carbonyl groups.

Savage *et al.* (1972) found that the captured volatilised products of heated cellulose appeared and behaved in a similar manner to the captured volatilised material from a repellent soil. They suggested that cellulose may be one source of the repellent material. However Roberts and Carbon (1972) found that an Australian sand remained repellent after extraction of the cellulosic fractions with acid solutions.

Giovannini and Lucchesi (1984) found that differential thermal analysis (DTA) revealed an exothermic peak at 490 °C in both a repellent clay loam and materials extracted with acetylacetone/benzene, but not in the extracted soil. They suggested that the 490 °C peak was diagnostic for repellency since the height of the peak correlated with the severity of repellency induced by each of the extracted fractions upon a nonrepellent sand. However the 490 °C peak was absent in a DTA study of a burned repellent soil in Scotland (Mallik and Rahman 1985). DTA studies may prove useful for elucidating properties of the repellent coating, but need to be conducted upon a wide range of soils.

Giovannini and Lucchesi (1984) used the infrared spectrum of the repellent extract to infer the nature of atomic bonding within the material. They found evidence of aromatic compounds, esters, polysaccharides, transolefinic hydrocarbons and methoxyl groups. They cited the presence of methoxyl groups as an indication that the repellent fraction had a low degree of humification.

Some contention has arisen over whether the repellent coating is within the humic or fulvic acid fraction. Miller and Wilkinson (1977) found that the organic coating surrounding dry patch sand grains produced an infrared spectrum closely resembling those of fulvic acids (Stevenson and Goh 1971). However Roberts and Carbon (1972) found that

the humic acid (HA) fraction and not the fulvic acid (FA) fraction of the organic coating induced repellency when added to a nonrepellent sand. Adhikari and Chakrabarti (1976) found that addition of one soil HA and two microbial HAs increased the repellency of an Indian soil (from WDPT 20 s to WDPT 73 - 160 s). The microbial HAs produced the greatest effect, which was increased slightly by the addition of iron. Nakaya *et al.* (1977b) added a range of soil HAs to a nonrepellent sand ($H = 0°$, Emerson and Bond 1963). All of the five HAs tested produced repellency in the sand (H 71 - 97°). Increasing HA concentrations upon the sand succesively reduced the capillary rise of water. In a contrasting study, Savage *et al.* (1969a) evaluated the effect of three microbial, one soil and one peat HA upon a nonrepellent sand and sandy loam. Only one of the microbial HAs produced slight repellency (WDPT $<$ 15 s) at soil pH 6 and they concluded that HA substances probably contribute little to repellency.

The soil humic fraction (HA and FA) represents a complex colloidal system consisting of molecules with a wide range of molecular weights (Stevenson 1982). The humic colloids have hydrophilic properties, however close association with soil particles may reduce their affinity for water due to changes in molecular orientation and the relative positions of charged sites. Debate regarding the relative contribution of HA and FA to repellency is somewhat unproductive because HA and FA are classified on the basis of extraction conditions and comprise many organic compounds.

A number of studies have implicated fatty with repellency. Wander (1949) suggested that alcohol extracts from repellent citrus soils indicated the presence of fatty acids. He found that stearic acid created extreme repellency in a nonrepellent soil after treatment with calcium and magnesium hydroxide and concluded that repellency was due to Ca and Mg soaps of fatty acids. Savage *et al.* (1969b) found that palmitic acid induced repellency in sands after heating. Ma'shum *et al.* (1988) found that palmitic acid and another highly polar lipid, cetyl alcohol induced severe repellency (MED c. 6) in an acid-washed sand without heating. Calculations with cetyl alcohol showed that measurable repellency only occurred after sufficient material was added to produce a close-packed monolayer on the sand grains. A 16-fold excess of material was necessary to produce maximum repellency which led Ma'shum *et al.* (1988) to suggest that the lipids may need to coat the surfaces of water droplets as well as soil particles.

Wilkinson and Miller (1978) speculated that Ca and Mg soaps of fatty acids were responsible for repellency due to the solubility properties of organic material extracted from repellent sites on golf greens. Tucker *et al.* (1990) rejected the speculation of Wilkinson and Miller (1978) because they measured no difference in the extractable Ca and Mg content between 'dry patch' and 'non-dry patch' cores. However, Wallis *et al.* (1989b) have found that 'non-dry patch' areas of a green (i.e. those areas not displaying the symptoms of repellency) have an equal repellency severity to the dry patch areas once dry, therefore the criticism of Tucker *et al.* (1990) is invalid.

Ma'shum *et al.* (1988) used spectroscopic and chromatographic examination of an *iso*-propanol/ammonia extract to identify 16-32 carbon atom, free and esterified fatty acids within the extracted material. The fatty acids had a bimodal distribution with maxima at C_{16} and C_{22} and comprised 1 - 18% of the extracted carbon. The ^{13}C-NMR and infrared spectra of the most hydrophobic extract suggested that molecules with extensive polymethylene chains were responsible. The infrared spectra were similar to previously published spectra for organic coatings extracted from sand grains of repellent golf greens (Miller and Wilkinson 1977), repellent soils (Giovannini and Lucchesi 1984) and repellent plant litter (McGhie 1980).

The role of fatty acids in other repellent soils deserves further research. The use of a standard extraction technique would facilitate comparisons between studies and the *iso*-propanol/ammonia solvent used by Ma'shum *et al.* (1988) appears to have advantages over other extractants used to date. Fatty acids comprised 1 - 18% of the extract in the study of Ma'shum *et al.* (1988). The characterisation of other components in the repellent coating would improve our understanding of repellency development and expression.

D. The Influence of Soil pH

Whether soil pH has an influence upon the development of repellency is uncertain. Van't Woudt (1959) found that lime application to repellent New Zealand soils successively reduced repellency. When 2 t ha^{-1} was worked into the 0 - 150 mm soil layer, repellency was removed, however the resulting pH values were not reported. Bond (1969a) reported

that calcareous and acid sands of Australia were equally affected by repellency. Savage *et al.* (1969a) found that repellency induced by addition of a microbial humic acid to a nonrepellent sand and sandy loam was influenced by pH, however the results were not consistent between the two mediums.

Two New Zealand scientists, Jackson and Gillingham (1985) reported that lime addition in several field trials produced rapidly increased soil moisture levels. They cited researchers in a range of districts who had reported similar observations. The moisture response was most evident in late summer/early autumn, and particularly after dry periods. They found that liming had reduced repellency as measured by capillary rise and water drop penetration time but proposed no mechanism for the effect.

A possible mechanism for the reduction of repellency by liming is as follows. Fulvic acid (FA) is soluble in water at any pH that may occur in soils, whereas humic acid (HA) is water soluble only at pH $>$ 6.5 (Chen and Schnitzer 1978). Furthermore, Chen and Schnitzer (1978) demonstrated that both HA and FA solutions significantly reduced the surface tension of water, which would decrease the solid-liquid contact angle and increase infiltration into repellent soil. The surface tension of HA and FA solutions also decreased with increased pH. Liming soil to increase pH would therefore increase the ability of resident FA (and HA at pH $>$ 6.5) to increase infiltration into repellent soil. Chen and Schnitzer (1978) noted that if there is a deficiency of FA in the soil solution, repellency would be more severe.

The balance between quantities of FA and HA in the soil may therefore be implicated in the development of repellency, along with soil acidification, however as reported earlier there is conflicting evidence regarding the contribution of HA and FA to repellency. FA is known to leach with soil development, because of its solubility across the pH range (Schnitzer and Desjardins, 1969). As soils develop, topsoil FA would tend to decrease (Goh *et al.* 1976) with a consequent increase in repellency.

Although increasing soil pH is relatively cheap and straightforward, any beneficial effect of repellency reduction must be balanced against the influence of soil pH upon soil biological activity and the availability of plant nutrients.

E. The Influence of Soil Relative Humidity

The reported effects of soil relative humidity (RH) upon repellency are inconsistent. At RH < 100% the repellency of dry sands has been found to increase, decrease or remain constant (Yuan and Hammond 1968; Jex *et al.* 1985; Roberts and Carbon 1971). At 100% RH the repellency of dry sands has been found to either increase (Jex *et al.* 1985) or decrease (Roberts and Carbon 1971). The repellency of sands wetted prior to incubation at 100% RH has been found to decrease (Roberts and Carbon 1971; Jex *et al.* 1985). The effects of humidity upon repellency should be regarded within the context of normal soil RH values. Soil RH exceeds 99.56% at matric potentials of less than -6 bars (Hillel 1980). Therefore unless the soil becomes very dry RH is always very close to 100% so that the studies which imposed very low RH values are irrelevant to field soil conditions.

F. The Effect of Fire

High temperatures have been used to render repellent soils nonrepellent (Emerson and Bond 1963). However DeBano (1969c) found that the relationship between heat and repellency was more complex. The repellency of a soil from a burned watershed greatly increased at > 200 °C but was destroyed at > 430 °C in a muffle furnace. Cory and Morris (1969) made similar observations, however other studies have found that repellency is lost at temperatures of 200 - 315 °C (DeByle 1973; Savage 1974; Scholl 1975; Nakaya *et al.* 1977a,b; John 1978).

Water repellency in burned soils was first recognised by workers at the University of California, Riverside (Osborn *et al.* 1964). Krammes and Osborn (1969) reported that 60% of the burned watersheds in Southern California which supported predominantly chamise chaparral bush *Adenostoma fasculatum* were repellent. Osborn *et al.* (1964) used a field wetting agent treatment to identify repellency as an important factor which influenced runoff, erosion and plant establishment in the burned watersheds. Since this time, repellency in burned soils has been reported in other states of America (Hussain *et al.* 1969; DeByle 1973; Scholl 1975; Reeder and Jurgensen 1979) and in other countries

including Japan, New Zealand, Italy and Scotland (Nakaya *et al.* 1977a,b; John 1978; Giovannini and Lucchesi 1983; Mallik and Rahman 1985).

Water repellency in burned soils differs from 'natural' repellency. In a naturally repellent soil hydrophobic material naturally accumulates and may take many years to reach significant levels (DeBano 1969d). 'Heat-induced' repellency can develop rapidly under wild fires or controlled burn-offs (John 1978). Fire may increase or decrease the existing natural repellency of a soil (Debano 1969c; Giovannini and Lucchesi 1983) or fire may induce repellency in soil which was previously nonrepellent. DeBano (1969c) found that burning plant litter over a nonrepellent sand induced repellency at depth in the sand. On unburned watershed areas, repellency was found only in the upper 50 mm layer (fig. 1.9). In lightly burned areas, the upper 25 mm of soil was essentially nonrepellent, and repellency was concentrated in the 25-75 mm layer. On the severely burned areas, repellency was not detectable in the first 65 mm of the profile and repellency appeared to have been translocated into the 75 to 150 mm layer. Reeder and Jurgensen (1979) found that the heat-induced repellency of Michigan forest soils occurred mainly within 0 - 50 mm depth but was occasionally found up to 150 mm depth.

DeBano (1969c) proposed that the mechanism of heat-induced repellency comprised volatilisation, downward distillation and condensation of repellent organic material. Giovannini and Lucchesi (1983) found that the organic matter in a burned repellent soil was decreased by 36% in the topsoil which they suggested was due to volatile loss. Organic matter in the subsoil increased by 50% but did not induce repellency which they suggested was due to the fine texture of the soil (clay loam topsoil, clay subsoil). DeByle (1973) found that upwards movement and deposition of organic material could also occur. Heating repellent coniferous litter at 315 °C removed the repellency of open soil samples but induced repellency at the surface of enclosed soil. Lower temperatures did not affect repellency and higher temperatures completely removed repellency from the open and enclosed soil. Scholl (1975) found that fires of temperature up to 270 °C at 5 mm depth induced repellency at the soil surface but a 331 °C fire made the soil surface nonrepellent and increased repellency at greater depth. Heating the soil in closed *vs* open containers showed that volatile material was lost from the soil at temperatures > 270 °C. Scholl (1975) contended that below 270 °C sufficient material was trapped and condensed within

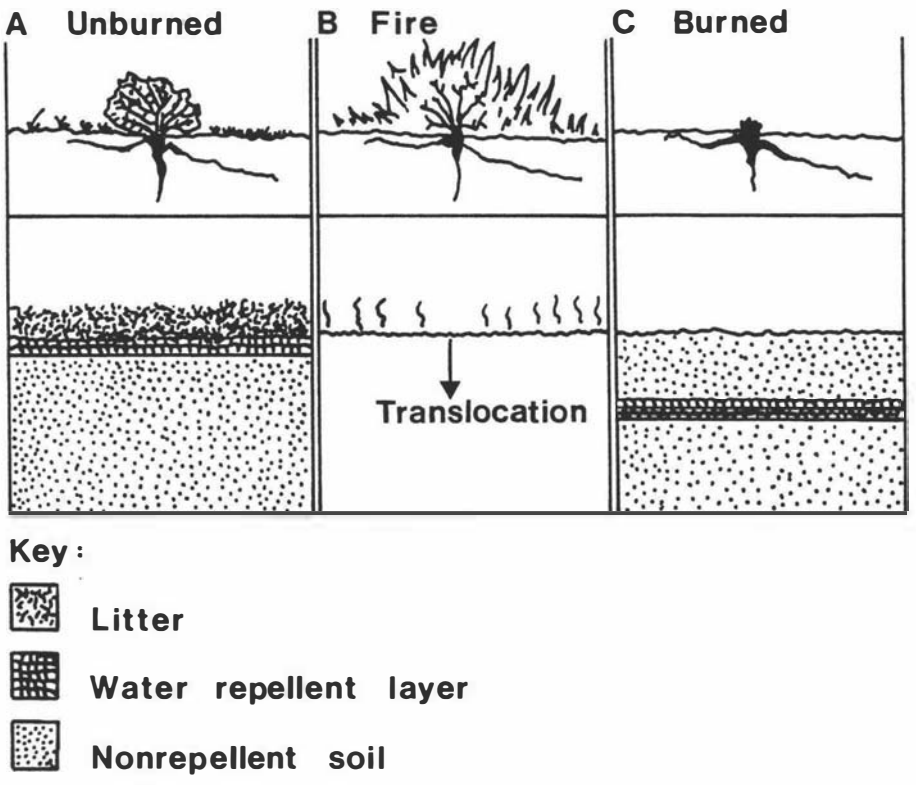


Figure 1.9. Water repellency before, during, and after fire. (A) Before fire the water repellent substances accumulate in the litter layer and mineral soil immediately beneath it; (B) fire burns vegetation litter layer, causing the water repellent substances to move downward along temperature gradients; (C) after a fire a water repellent layer is located below and parallel to the soil surface. After DeBano (1969c).

the soil to increase surface repellency.

Savage *et al.* (1969b) found that the substance responsible for repellency of fungal sand cultures was not extractable after heating but was extractable under the same conditions before heating which indicated that a heat-induced chemical change in the substance had occurred. Savage *et al.* (1972) captured volatile substances released from a burned soil which was susceptible to heat-induced repellency. The captured substances induced some degree of repellency when added to a nonrepellent sand, however they induced severe repellency when heated on the sand at 300 °C for 10 minutes. Savage (1974) found that the primary movement of organic substances from burning litter into underlying soil occurred during fire and induced natural fractionation of the substance. Heating at over 300 °C decreased the ease of extracting the fractions, which lended support to Savage's (1969b) theory of *in situ* heat 'fixing'. The remainder of material which was not 'fixed' was volatilised at 300 °C.

The effect of fire temperature appears to be site-specific and may depend upon the nature of the burned material (section IV.F). Savage *et al.* (1969b) measured the heat-induced repellency of 10 naturally repellent soils found under a range of vegetation. Variable effects of heat and solvent extractants led Savage *et al.* (1969b) to suggest that a range of substances were responsible for repellency in the soils. DeBano *et al.* (1976) found that the severity of heat-induced repellency was not simply related to the %C of the organic matter deposited on the soil which supported the theory of DeBano *et al.* (1970) that only a fraction of the translocated organic matter was responsible for repellency.

Soil texture, water content and the time of burning have been found to affect heat-induced repellency. DeBano (1969c) reported field observations that the thickest and most severely repellent layers were usually found in coarse-textured soils. DeBano *et al.* (1970) found that the thickness of the repellent layer induced by burning plant litter over a range of soils was increased as the proportion of silt and clay decreased. DeBano *et al.* (1976) found that a short burn over dry sand produced the most severe repellency. A longer burn translocated the repellent materials deeper in the sand but removed surface repellency. Burning over wet sand concentrated repellency in the surface layer.

Like natural repellency, heat-induced repellency is spatially variable. DeByle (1973) found that 5% of 0 - 50 mm soil samples from a coniferous Montana forest were repellent (WDPT > 5 s) before fire, but 30% were repellent after fire. Reeder and Jurgensen (1979) reported that 23% of 0 - 150 mm soil samples from unburned forest plots were repellent (WDPT > 10 s), but 40% of samples removed from 53 fire sites with a range of vegetation and soils were repellent. Krammes and Osborn (1969) reported that burned chapparal soil had a high spatial variability of moisture content.

It would appear that heat-induced repellency may be relatively short-lived. DeByle (1973) found that one year after fire the number of repellent samples tested had declined from 30% to 7%. Reeder and Jurgensen (1979) found that most (65%) of the soils which were repellent after fire were nonrepellent after one year. DeBano and Rice (1973) reported that repellent layers had been found in soils > 10 years after fire but suggested that repellency was greatly reduced after one year and became negligible after 5 - 10 years.

A number of techniques have been suggested for the management of soils with heat-induced repellency. DeBano and Rice (1973) suggested that a cool- burning fire would minimise repellency severity or slash could be piled to concentrate the problem. DeBano *et al.* (1976) suggested that the least repellency-forming conditions of a short burn over wet soil could be attained by dessicating standing brush and burning when the soil is wet. DeBano and Rice (1973) suggested that the repellent layer could be broken up with a seed drill or 'sheepsfoot roller' if terrain permitted. DeBano and Rice (1973) evaluated wetting agents for alleviation of heat-induced repellency but found that the chemicals at the rates used were unsuccessful. In contrast Osborn *et al.* (1964) found that a wetting agent was effective and resulted in 'a very favourable benefit to cost ratio' (Krammes and Osborn 1969). A comprehensive discussion of wetting agents is given in section V.C.

G. Spatial and Temporal Variability

An important aspect of repellency development is high spatial variability of expression. Bond (1964) found that the moisture content within a repellent soil after rainfall varied from 1 to 8 % over 10 mm distance. Wallis and Horne (unpub. data) have measured

moisture content differences of even greater magnitude over 50 mm distances in repellent sands. Mallik and Rahman (1985) reported high variability in the WDPT of an undisturbed podzolic soil. Highly variable WDPT and MED values on undisturbed soil samples have been measured by Wallis and Horne (unpub. data).

A number of studies have found that rain or irrigation water penetrates repellent soils through channels and leaves the remainder of the soil dry (Jamison 1945; Bond 1964; Gilmour 1968; Hendrickx *et al.* 1988a,b). Hendrickx *et al.* (1988a,b) found that the channels were initiated at soil surface locations where repellency was least. The channels effectively created preferential flow pathways for water and solute movement which extended into the subsoil. Raats (1973) described the theory whereby repellent soil may cause wetting front instability which leads to the development of preferential flow pathways.

The cause(s) of high spatial variability of repellency are unknown, but may include the nature and distribution of past and/or present vegetation species and microbial populations (section IV.B). Micro-scale variability (over a few mm or cm) may be due to microtopographic, physical and chemical variability (Bond 1972; Mallik and Rahman 1985). Regardless of the possible causes, high spatial variability of repellency causes patchy plant establishment and growth (Bond 1972) and makes field research difficult (Wallis *et al.* 1990b).

Water repellency expression may vary over time because repellency is expressed most strongly when the soil is dry (DeBano 1971). However a number of studies have found that zones of soil may remain dry and repellent throughout extended periods of rainfall (Jamison 1945; Bond 1964; Hendrickx *et al.* 1988a,b). Hendrickx *et al.* (1988a,b) took soil moisture measurements over winter which demonstrated that the dry, repellent zones of soil wetted by capillary rise as the water table rose rather than by direct rainfall infiltration. Topography may affect the seasonal expression of repellency through both the soil position in relationship to the water table and the influence of slope angle upon surface water redistribution.

V. AMELIORATION OF REPELLENCY

A. Cultivation

Cultivation to ameliorate repellency has been recommended to dilute the repellent soil fraction with nonrepellent soil (Holzhey 1969a). Cultivation may also cause abrasion of repellent soil particles. Ma'shum *et al.* (1985) and Wallis *et al.* (1990a) found that abrasion of repellent sand in end-over-end shakers significantly reduced repellency (fig. 1.10). However Wallis *et al.* (1990a) found that the repellency of the shaken sand increased somewhat after standing, which they proposed was due to changes in the molecular conformation of the organic matter responsible for repellency. They pointed out that this may limit the opportunities for using cultivation as a field treatment for repellency, and that in soils such as the one studied a deep layer of severely repellent soil would limit the practicality of dilution recommended by Holzhey (1969a). Furthermore, repellent sands are often prone to wind erosion when cultivated and dilution of the topsoil would reduce the water and nutrient holding capacity of the surface soil.

B. Amendment of Soil Texture

Clay amendments were used by Dutch farmers in the 1950s to improve holding capacity, prevent wind erosion and reduce repellency. (Hendrickx *et al.* 1988b). Jamison (1945) found that mixing repellent soil with 'wettable' soil greatly reduced or eliminated repellency. Roberts (1966) found that only 2.5% of three fine-particle amendments (fly ash, clay and finely ground silica) were necessary to overcome the effects of repellency upon seedling emergence in an Australian sand. McGhie and Posner (1981) reported that the incorporation of 3% silt/clay effluent from an Alumina refinery was sufficient to lower the WDPT of a sand from minutes to seconds. Addition of the fine particles may enable relatively long-term control of repellency because the high specific surface area particles would be less readily coated by a hydrophobic organic coating (McGhie 1987).

Recently Ma'shum *et al.* (1989) have found that the addition of sodic kaolinite and illite clays reduced the repellency of a natural and a synthetic repellent soil. The equivalent of

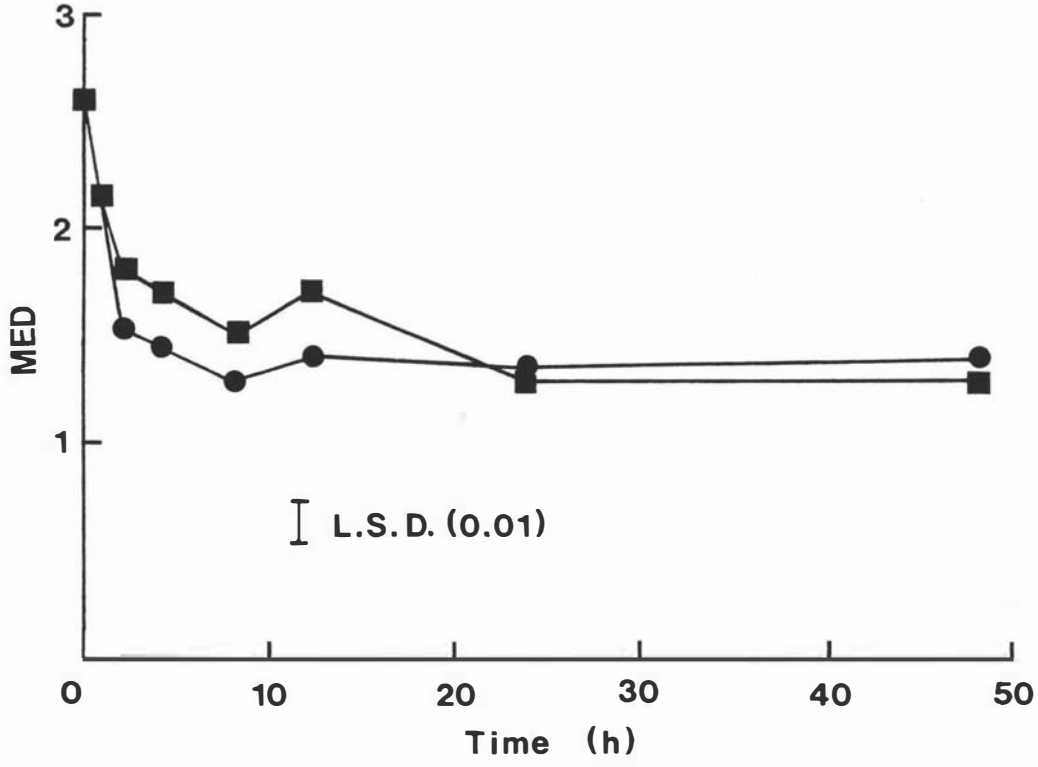


Figure 1.10. Water repellency (Molarity of Ethanol Droplet, MED) of air-dry Himatangi sand immediately after periods of agitation in an end-over-end shaker (●) and at 72 h after agitation commenced (■). After Wallis *et al.* (1990a).

2.5 to 5 tonnes ha^{-1} to 100 mm depth was required to make a severely repellent sand nonrepellent. Many repellent soils in South Australia have sodic clay subsoils, which may be displaced to the soil surface using a specially designed plough implement. Field evaluation of this technique is currently being conducted (Oades pers. comm.). For intensive horticulture such as sports turf, natural sodic clays or clays fortified with sodium could be imported and incorporated in the growth medium or used as a texture amendment. The viability of such techniques would be subject to the availability of sodic clays and the cost and practicality of its incorporation in the root zone mix.

Waddington (1969) noted that topdressing sports turf with soil and/or the removal of small cores had been shown to decrease the incidence of soil repellency. Bond (1978) investigated the addition of cores of nonrepellent sand and sandy loam to overcome repellency in turf on sandy soils. He found that coring (core holes 15 mm diameter, 75 mm deep and 50 mm apart) without backfilling increased water infiltration rates and reduced the visible occurrence of dry patch for $<$ 18 months. Addition of sand to the core holes was also beneficial for $<$ 18 months, while addition of sandy loam produced beneficial effects for $>$ 30 months. He pointed out that the use of fine textured soil on golf greens would not be readily accepted because of potential drainage problems, but noted that these problems should not occur if the soil is added in narrow vertical columns (cores) rather than in a continuous layer. Furthermore, addition of silt and/or clay would increase the water holding capacity of the soil. Wilkinson and Miller (1978) and Danneberger and White (1988) have found that wetting agent application in conjunction with coring was more effective than coring alone.

C. Soil Wetting Agents

Wetting agents are surfactant chemicals used on repellent soils to increase water infiltration (Watson 1969). Due to their cost wetting agents have been principally used in turf culture. The addition of a wetting agent to a solution will decrease the surface tension of the liquid in the same manner as ethanol addition in the NDST and MED repellency tests (section III.E,F). Decreased liquid surface tension will decrease the infiltration rate into a nonrepellent soil. Pelishek *et al.* (1962) found that a wetting agent reduced

infiltration into a clean quartz sand with an apparent contact angle, $H = 43^{\circ}$ (Letey *et al.* 1962a). However in repellent soils surfactant application will also lower the liquid-solid contact angle. This beneficial effect will outweigh the detrimental effect of decreased surface tension, and the infiltration rate of the solution containing the surfactant will be increased (Mustafa 1969). Miyamoto (1985) found that wetting agents improved infiltration into natural soils with H 56 - 81° which indicated that wetting agents may be effective for soils which appear nonrepellent (low H and WDPT).

In addition to the initial improvement in the infiltration rate, an effective wetting agent must also have a residual effect (Pelishek *et al.* 1962; McGhie 1987) which will maintain increased water infiltration rates. Letey *et al.* (1962b) found that initial infiltration into an extremely repellent soil was more rapid for wetting agent solutions than for water. Subsequent water applications to plots treated with wetting agent also infiltrated more rapidly. Wetting agents vary in their effect upon infiltration. McGhie and Tipping (1984) found that only 4 of 42 products tested were very effective at increasing the initial infiltration rate and producing a residual effect. The effectiveness of wetting agents was found to be dependent upon the application rate used and may also be affected by the dilution rate used for application (Wallis *et al.* 1990b).

By increasing water infiltration into repellent soil, effective wetting agents have been shown to increase plant establishment and growth (Osborn *et al.* 1964; Osborn *et al.* 1967; Osborn 1969; Wallis *et al.* 1990b). Wetting agents may be used to reduce runoff and subsequent erosion. Osborn *et al.* (1964, 1967) found that a wetting agent treatment reduced debris movement by 95% and surface runoff by 32% from five small storms of moderate intensity on a hill soil in Southern California. Grass establishment was improved four-fold by wetting agent treatment, and the stabilising effect of the vegetation was found to reduce erosion in the longer term.

The chemistry of wetting agents determines their effects upon infiltration and other soil properties. Wetting agent molecules exhibit amphipathic character, that is they contain a hydrophobic hydrocarbon group and a polar group which is hydrophilic. This gives rise to amphipathic adsorption, in which the hydrophobic groups are oriented away from the water and the polar groups toward it (Black 1969). When the linear, hydrophobic portion

of the molecule forms the anion in aqueous solution, it is said to be anion-active or anionic. If the molecule ionises so that the hydrophobic portion forms the cation, it is cationic. The nonionic class is characterised by nonionised hydrophilic end-groups that are usually polar-active in nature (Law and Kunze 1966). Nonionics have been most widely adopted for soil application because they are least phytotoxic and the degree of solubilisation, which is important in controlling adsorption behaviour, can be varied more precisely than with ionic compounds (Black 1969). Nonionics may not be the ideal class of surfactant in media other than soil. Miyamoto (1978) found that an anionic wetting agent out-performed two nonionic wetting agents for application to repellent coal mine spoils.

Wetting agent properties depend upon the size and polarity of the hydrophilic and hydrophobic groups in the molecule. The HLB value is an index of the balance between the hydrophilic and lipophilic (lipid-loving or hydrophobic) groups in a molecule. Black (1969) reported that wetting agents require an HLB of 7 - 9. Weil *et al.* (1979) tested a range of polyethoxylate chemicals and confirmed that the best wetting agents had HLB values of 7 - 9. In contrast McGhie and Tipping (1984) found that several chemicals with HLB 7 - 9 were totally ineffective. However, most of the effective wetting agents had an HLB of 8.3 - 8.5.

Wetting agents may have phytotoxic effects due to foliar contact or root uptake. Kaufman and Williamson (1981) found that soil applications of two nonionic wetting agents reduced the stomatal number and/or conductance of *Poa pratensis* turf grass. Petrovic *et al.* (1985) found that a nonionic wetting agent applied at normal application rates to *Poa annua* sports turf reduced seed formation by 73% on average. The wetting agent was not washed off the leaves and despite the apparent plant growth regulatory effect did not decrease the visual quality rating nor the clipping yield of the turf. Effron *et al.* (1990) cited a range of turf grass research which has shown that wetting agent phytotoxicity such as turf discoloration and leaf tip burn have resulted from the use of high application rates, especially under hot humid conditions, when low dilution rates and/or no watering in have been used (fig. 1.11). Wetting agents may be applied at rates exceeding recommended label rates with little risk of phytotoxicity provided that the chemical is washed off the leaves within a few minutes of application (Karnok and Tucker 1989).



Figure 11. Discoloration of turf grass due to the phytotoxicity of a wetting agent applied during hot, dry conditions without subsequent irrigation (photo M.G. Wallis).

Phytotoxicity due to root uptake may be difficult to avoid compared to problems arising from foliar contact. Parr and Norman (1964, 1965) showed that nonionic surfactants can inhibit root elongation when applied to soil at low concentration. Endo *et al.* (1969) found that two nonionic surfactants were more toxic in solution culture than in soil. The effects included shoot growth and rooting depth inhibition, and reduction of seed germination. Surfactant adsorption was assumed to account for the reduction in toxicity in soil since the most strongly adsorbed wetting agent was the least phytotoxic. They concluded that the critical factor determining the degree of phytotoxicity in a soil system is the extent to which the surfactant is adsorbed by the soil.

Law and Kunze (1966) and Law *et al.* (1966) found that nonionic wetting agents were adsorbed by kaolinite clay in amounts somewhat greater than anionics but less than cationics. Montmorillonite clays were found to adsorb the most wetting agent which was attributed to the oxygen ions of the mineral surface hydrogen-bonding with the polar-active groups of the nonionic compounds. Nonionics were adsorbed with greater energy than that of water and thus displaced water from the surfaces. Valoras *et al.* (1969) found that adsorption of nonionic wetting agents increased to a maximum with increasing wetting agent concentration and then levelled off. Greater adsorption occurred on soils with a higher specific surface. The limited adsorption capacity of sandy soils may cause wetting agent phytotoxicity in sports turf or naturally repellent soils, however such effects have not been investigated. Fortunately, a number of wetting agents used in turf are known to be strongly adsorbed, even to sandy loam soil (Miller *et al.* 1975).

Wetting agent adsorption has also been found to affect the degree of leaching and hence longevity in the soil. Valoras *et al.*(1969) found that one nonionic wetting agent appeared to be irreversibly adsorbed because none of the adsorbed chemical could be leached. Another nonionic was leached until a minimum adsorbed concentration was reached, after which very little was removed by further leaching. Miller and Letey (1975) studied the same chemicals and made similar observations. On the basis of a leaching study Krammes and DeBano (1967) suggested that one wetting agent may remain effective for at least one year in California. Osborn *et al.* (1969) evaluated the longevity of a range of nonionic and ionic wetting agents applied to repellent peat pots which were periodically leached over a period of three years. The effectiveness of all of the wetting agents was found to decline

over the three years, however all products retained some effect throughout the experiment.

Field testing is necessary to ascertain wetting agent longevity because the prevailing chemical, biological and physical conditions may differ to those in laboratory experiments (Wallis *et al.* 1990b). Wetting agents are biodegradable and therefore application must be repeated over time to ensure continued effectiveness. The effective life of wetting agents applied to turf or natural soils in field experiments has received little attention.

Mustafa and Letey (1969) found that the application of two wetting agents either before or with irrigation water decreased the aggregate stability of a repellent sandy loam. The wetting agents also decreased the aggregate stability of nonrepellent soil when applied with the irrigation water, but the residual effect increased the aggregate stability of a nonrepellent sandy loam and clay loam. Mustafa and Letey (1969) pointed out that the favourable effect of wetting agents upon the liquid-solid contact angle of repellent soil would normally overshadow the aggregate destabilising effect. Furthermore, limited soil structural development in sandy soils would reduce the importance of any wetting agent effect upon structure. In structured soils, these effects may be more significant.

Wetting agents have also been found to affect soil hydraulic conductivity (K). Watson *et al.* (1969) found that high concentrations (500 and 5000 ppm) of wetting agent decreased K of salt-affected soils significantly, which they suggested was due to clay swelling and dispersion. However, low wetting agent concentrations did not affect K. Miller *et al.* (1975) found that wetting agents did not affect K of a wettable soil, but decreased K of a repellent soil. Higher surfactant concentrations reduced K to greater degrees. The authors assigned this effect to the formation of wetting agent micelles which could block soil pores, aggregate destabilisation and particle migration.

The effect of wetting agents upon evapotranspiration is unclear. Morgan *et al.* (1966) found that a wetting agent did not significantly affect evapotranspiration from turf. In contrast, Law (1964) found that a wetting agent reduced evaporation from a bare soil surface by 50%. The contrasting findings may be due to the absence of a plant cover in Law's (1964) study. He suggested that the wetting agent probably reduced capillary flow

of water to the surface layer of the soil and caused the formation of a dry diffusion barrier.

McGhie (1983) developed a method in Australia for wetting agent use in 'broad-acre' agriculture. He applied wetting agent in bands behind a direct drill to reduce the volume of surfactant applied. Nonionic surfactant was applied at 20 l ha^{-1} (within-band application), which gave an actual usage of 3-4 litres per hectare. Several wetting agents were found to improve plant establishment on repellent sands at a number of sites using this technique. McGhie considered that the band-spraying technique had excellent potential, but commented that farmers should experiment with their own soil to find the optimum rate required. Wallis *et al.* (1990b) found that two band-sprayed wetting agents increased pasture growth in a repellent New Zealand sand.

The advantages of using wetting agents for amelioration of repellency in sports turf or natural soils should outweigh any disadvantages if correct application techniques are used. However questions remain regarding root-uptake phytotoxicity and the effects of wetting agents upon evaporation. Although wetting agents may be effective they are expensive and provide only temporary control of soil repellency.

D. Irrigation

In certain agronomic and turf systems, irrigation may be used to maintain soil in a moist state and thereby avoid the expression of repellency which develop as the soil dries (DeBano 1971; Bond 1964; Wallis *et al.* 1990a). In sports turf, irrigation and syringing (light watering used primarily to reduce turf heat-stress) are employed to maintain adequate soil moisture levels during hot dry periods and reduce the severity of dry patch (Danneberger and White 1988; Moore 1981). Wallis *et al.* (1989b) found that 'dry patches' on New Zealand golf courses were related to areas receiving poor irrigation coverage (fig. 1.12). They suggested that the uniformity of irrigation water application is an important determinant of 'dry patch' development, and that no amount of applied wetting agent would overcome the problem if a poorly designed and/or managed irrigation system was in place. It may be for this reason that Tucker *et al.* (1990) found no

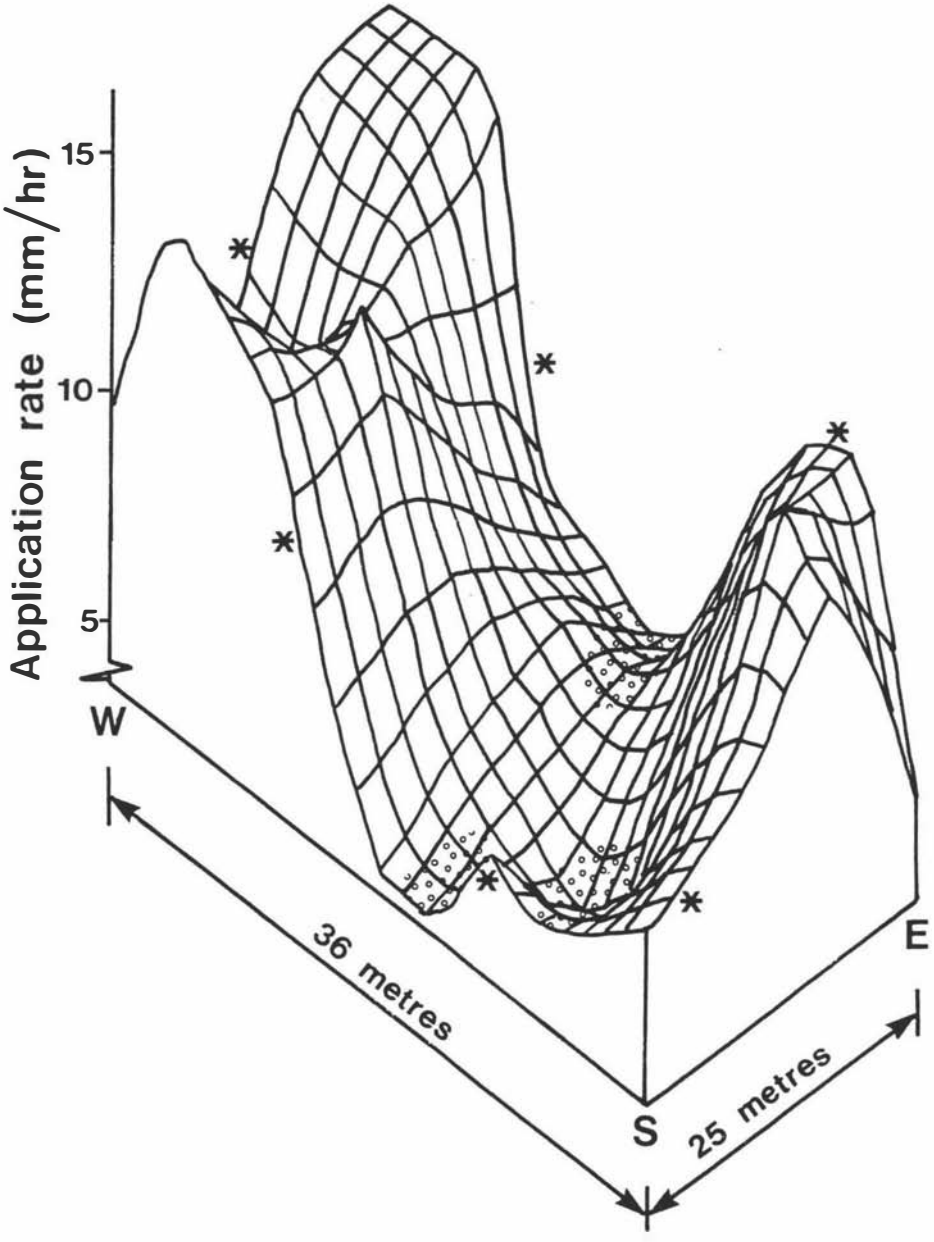


Figure 1.12. Contour map of the irrigation application rate on green 11, Manawatu golf course, Palmerston North, New Zealand. Shaded zones represent dry patch areas, which occurred in the areas of low application rate. The positions of sprinkler heads are indicated (*). After Wallis *et al.* (1989b).

relationship between dry patch severity and the use of wetting agents in a survey of golf courses in Georgia, U.S.A. Wallis *et al.* (1989b) pointed out that irrigation needed to be scheduled to match plant requirements, the soil should not be allowed to dry out early in the growth season, and frequent, light irrigations which only wet the thatch and surface soil layer should be avoided.

Wallis *et al.* (1990b) investigated the interaction of irrigation with the use of wetting agents upon a severely repellent sand. They found that delays of up to 14 days until initial irrigation following wetting agent application did not reduce the effectiveness of two wetting agents in a glasshouse. However they pointed out that delays between wetting agent application and initial irrigation in the field could reduce wetting agent performance due to ultra-violet light degradation and soil displacement by wind. Shorter irrigation return intervals consistently improved plant growth in untreated and wetting-agent treated repellent sand. Wallis *et al.* (1990b) noted that, so long as each watering is adequate, short return intervals would have facilitated infiltration into the repellent sand by maintaining higher surface soil water contents. They pointed out that, in contrast to turf irrigation and other intensive horticultural enterprises, short irrigation return intervals are often impractical and uneconomic in extensive agriculture. Wallis *et al.* (1991) also pointed out that the effects of repellency are likely to be most pronounced under irrigation systems with high application rates.

VI. CONCLUSIONS AND FUTURE RESEARCH PRIORITIES

Soil water repellency has been found to affect water movement into and within many soils. Recent research suggests that all soils may be repellent to some degree, challenging the common perception that repellent soils are only an interesting aberration. The dramatic effects of severe repellency upon infiltration, subsequent surface water redistribution and plant growth are readily observed and have been well-documented. However less severe repellency may produce sublime effects which are nonetheless hydrologically significant. Further research is warranted to quantify such effects; in particular the generation of preferential flow pathways, given worldwide concern over groundwater contamination. The effect of repellency upon evaporation also requires

clarification.

Many techniques for repellency measurement have been developed. The WDPT test is most simple but is unsuitable for severely repellent soil. Contact angle measures have no physical significance and are generally time-consuming. Infiltration measures generally must be related to comparative, 'nonrepellent' soil and thermal analysis techniques provide only semi-quantitative data. The MED test is well-suited for rapid assessment of severely repellent soil. The RI is somewhat more involved than the MED test but has greater sensitivity and provides measurements of practical significance to infiltration. Standardisation of measurement techniques would greatly facilitate research comparisons.

The development of natural or heat-induced repellency will not be fully understood until the precise nature of the hydrophobic organic coatings on soil particles is known. Isolating and identifying the components responsible for repellency will be difficult. Soxhlet extraction using *iso*-propanol/ammonia looks promising, although this procedure has yet to be tried upon a wide range of soils. However, once the compound(s) are identified it may be possible to trace their origin to plant and/or microbial species. Knowledge of the chemical nature of the hydrophobic coatings should also help to explain the extreme spatial and temporal variability of repellency.

The options for repellency control are often constrained by economic considerations. Wetting agents provide temporary relief, however further research of longevity and phytotoxicity is required. Soil texture amendment has the potential for longer-term benefits and is the subject of ongoing research. Irrigation may be used to avoid repellency expression by maintaining the soil water content above a critical level. Irrigation is also normally used in conjunction with wetting agent treatments. The irrigation water must be applied evenly and due consideration should be given to the application rate and return interval. Complete control of repellency may not be possible until its development is fully discerned.

CHAPTER TWO: WATER REPELLENCY OF THE HIMATANGI SAND

2.0 INTRODUCTION

Yellow-brown sands comprise c. 85 000 ha of the west coast of the lower North Island of New Zealand (Cowie 1963), and they are also found in other coastal areas of the North and South Islands. The sand country of the lower North Island west coast comprises a complex of dunes, sand plains, peaty swamps and lakes (Cowie 1968). The Himatangi sand is found on elevated sand plains of the area and is used principally for extensive agriculture.

A dairy farmer with predominantly Himatangi sand approached the soil science department in the mid-1980s because his recent investment in irrigation was not producing the expected gains in pasture dry matter production. Soil fertility tests did not indicate that nutrients were limiting production, and simple field investigations revealed that repellency may have been restricting the infiltration of irrigation water. The research described in this chapter sought to quantify repellency and evaluate means for overcoming the problem.

2.1 A STUDY OF WATER REPELLENCY AND ITS AMELIORATION IN A YELLOW-BROWN SAND. 1. SEVERITY OF WATER REPELLENCY AND THE EFFECTS OF WETTING AND ABRASION.

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Abstract

Water repellency of Himatangi sand was assessed by in situ water infiltration measurements and in the laboratory using the Molarity of an Ethanol Droplet (MED) technique. Infiltration rates on water repellent areas were an order of magnitude lower than rates on adjacent, less repellent areas. The surface (30 mm) soil of cores removed from repellent areas was severely repellent (MED > 2.2), and soil to a depth of 150 mm was moderately repellent. MED was strongly correlated with soil carbon content (R^2 = 0.79).

Attempts were made to overcome repellency by wetting the soil and by abrasion. The water repellency of Himatangi sand increased when the gravimetric soil water content, w was increased from w = 0.03 to w = 0.05 and then declined rapidly with further increases in soil water content. Air dry samples were agitated in an end-over-end shaker for a range of 1 to 48 hours. Soil water repellency was significantly ($P < 0.01$) reduced by up to 8 hours agitation. Water repellency of samples which had been shaken for 2, 4, 8 and 12 hours significantly ($P < 0.01$) increased after standing until 72 hours had elapsed.

INTRODUCTION

Soil water repellency is an important hydrological consideration in many regions of the World (De Bano and Letey 1969). Water repellent soils exhibit hydrophobic properties when dry, resisting water infiltration into the soil matrix (Brandt 1969a). Runoff and erosion can be significantly increased in catchments containing water-repellent soils (De Bano 1969b,c; Krammes and Osborn 1969; McGhie 1980). Osborn *et al.* (1964, 1967) found poorer vegetation establishment on a water repellent site because less water entered the profile and seeds were physically removed by erosion.

Development of organic coatings on soil particles is thought to be the main cause of hydrophobicity (Fink 1970; Savage *et al.* 1972). Water repellency has been related to particular forms of vegetation and to soil fungi (Richardson and Hole 1978; Savage 1969). The specific nature of the organic coating has been studied intensively by Ma'shum *et al.* (1988) who showed that free and esterified long-chain fatty acids are partly responsible for the hydrophobicity of an Australian soil. Water repellency can also be induced in some soils after fire (De Bano *et al.* 1970; John 1978).

Sandy soils have been found most susceptible to severe repellency problems. Because of their low specific surface, sand particles are more readily coated with the hydrophobic organic substances (De Bano *et al.* 1970). Aggregated clay soils can also exhibit water repellency (McGhie and Posner 1980).

A number of methods have been used to ameliorate the water repellent condition. Cultivation was recommended by Holzhey (1969a). He considered that the dilution of the repellent soil fraction with non-repellent soil would allow water infiltration into the profile. Cultivation may also cause abrasion of water repellent sand grains. Ma'shum and Farmer (1985) have proposed that abrasion removes the organic coating from sand particles to reduce repellency.

The Himatangi sand, a Yellow Brown Sand found on the west coast of the lower North Island, suffers from water repellency in the topsoil, which adversely affects pasture and

crop establishment and production. Himatangi sand is found on sand plains where the water table rises to the lower part of the subsoil in winter. (Cowie *et al.* 1967; Cowie and Rijkse 1977). Swain and Scotter (1988) determined that the Himatangi sand contained 95 - 99% sand, 85% of which was 0.25 mm to 0.125 mm in diameter. They found that soil bulk density increased from 1.2 Mg m^{-3} in the top 50 mm to 1.5 Mg m^{-3} between 500 and 1000 mm depth. Swain and Scotter (1988) provided soil water retentivity data for the Himatangi sand and cited organic carbon levels of 1.98 $\pm$ 0.28% in the top 100 mm and 1.07 $\pm$ 0.48% between 100 and 200 mm depth. Cowie *et al.* (1967) provided a chemical analysis of the Himatangi sand. Cation exchange capacity ranged from 13 meq % (0-250 mm) to 2 meq % (200-650 mm) and base saturation from 64 to 86%.

A research programme has been initiated by the Department of Soil Science, Massey University, to quantify water repellency of the Himatangi sand and investigate strategies for alleviating this soil condition. This paper reports an evaluation of soil water repellency and the effect of abrasion on the water repellency of this soil.

MATERIALS AND METHODS

The experimental site, used for all field trials and sampling, is located 1.2 km east-south-east of Himatangi (NZMS reference N148/842304). The pasture sward at the site was predominantly *Lolium perenne* and *Trifolium repens* with significant populations of *Trifolium subterraneum* and *Agrostis* spp.

Assessment of Soil Water Repellency

MED and % Carbon Profiles

Twenty cores were taken from an eight hectare area of Himatangi sand. Each core was divided into 0-30, 30-60, 60-90, 90-150 and 150-200 mm depths, air dried (gravimetric water content, $w \sim 0.02$) and sieved to 2 mm.

Samples were evaluated for water repellency using the Molarity of Ethanol Droplet (MED) test, first proposed by Watson and Letey (1970) and developed by King (1981). The MED test measures the molarity of an aqueous ethanol droplet required for soil infiltration within 10 seconds. Ethanol lowers the liquid surface tension, enabling infiltration. King (1981) provided the following guidelines for interpretation of MED values: MED = 0, non-repellent; MED < 1, low repellency; MED 1.0 - 2.2, moderate repellency; MED > 2.2, severe repellency.

Subsamples of approximately 10 g were placed in petri dishes and lightly pressed flat. MED was tested using an eye-dropper, stop watch and ethanol solutions ranging from 0 to 5 molar in 0.2 M increments.

Subsamples of c. 0.5 g were placed in a Leco induction furnace to determine the carbon content at each depth (Nelson and Sommers 1982).

Infiltration

Two sites were selected to represent severely repellent and less repellent Himatangi sand. The two sites were less than 10 m apart, however the severely repellent site was more elevated (approx. 400 mm) and supported a plant population dominated by drought resistant weeds. A disc permeameter, developed recently by Perroux and White (1988), was used to measure soil water infiltration with a 10 mm positive head. Three observations were made at each site.

Physical Techniques for Reducing Soil Water Repellency

Effect of soil water content on MED

Four replicates of air-dry Himatangi sand (MED = 2.9) were placed in petri dishes and slowly wetted up with minimal mixing to produce successively greater gravimetric water contents. MED was assessed at each water content until MED = 0.

Effect of abrasion on MED

Ma'shum and Farmer (1985) investigated the effect of abrasion by shaking a soil-water mixture (25 g/100 cm^3). They measured a reduction in soil water repellency which may have been caused by abrasion, by sand wetting, or by a combination of wetting and abrasion. To study the effect of abrasion specifically, air dry Himatangi sand was agitated. Twenty-eight centrifuge tubes, each filled with 10 g of sand (MED = 2.6) were placed in an end-over-end shaker. Four tubes were removed from the shaker after 1, 2, 4, 8, 12, 24 and 48 hours of shaking and soil MED assessed. Soil MED was reassessed on these samples (undisturbed since removal from the shaker) at 72 hours.

RESULTS AND DISCUSSION

Assessment of Soil Water Repellency

MED and % Carbon Profiles

Soil MED values declined with depth and were strongly correlated (R^2 = 0.79) with soil carbon content (Fig. 2.1). Severe water repellency was restricted to the top 30 mm of soil where the carbon content was 5.1%. Moderate water repellency was found between 30 and 150 mm depth, with slight water repellency between 150 and 200 mm depth. The fact that relatively low organic matter levels below 100 mm depth produced water repellency illustrates the relationship between soil texture (and hence specific surface) and the development of the hydrophobic organic coating (De Bano *et al.* 1970).

Infiltration

The severely water repellent site had a significantly lower ($P < 0.01$) infiltration rate than the less repellent site (the equivalent of 36.6 mm h^{-1} compared with 204 mm h^{-1}) (Fig. 2.2). De Bano (1971) reported that infiltration in wettable soil can be as much as 25 times faster than that in similar water repellent soil. Although the infiltration rate of a water repellent soil may increase after 30 minutes of measurement (De Bano 1969a), the

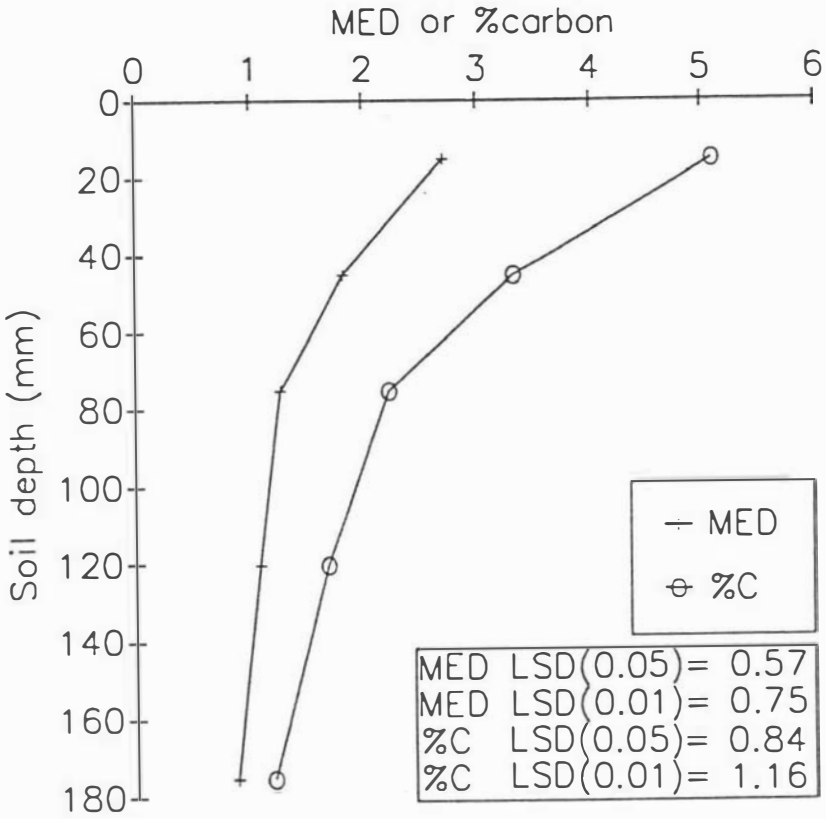


Figure 2.1. Carbon content (%) and water repellency (Molarity of Ethanol Droplet, MED) profiles of the Himatangi sand.

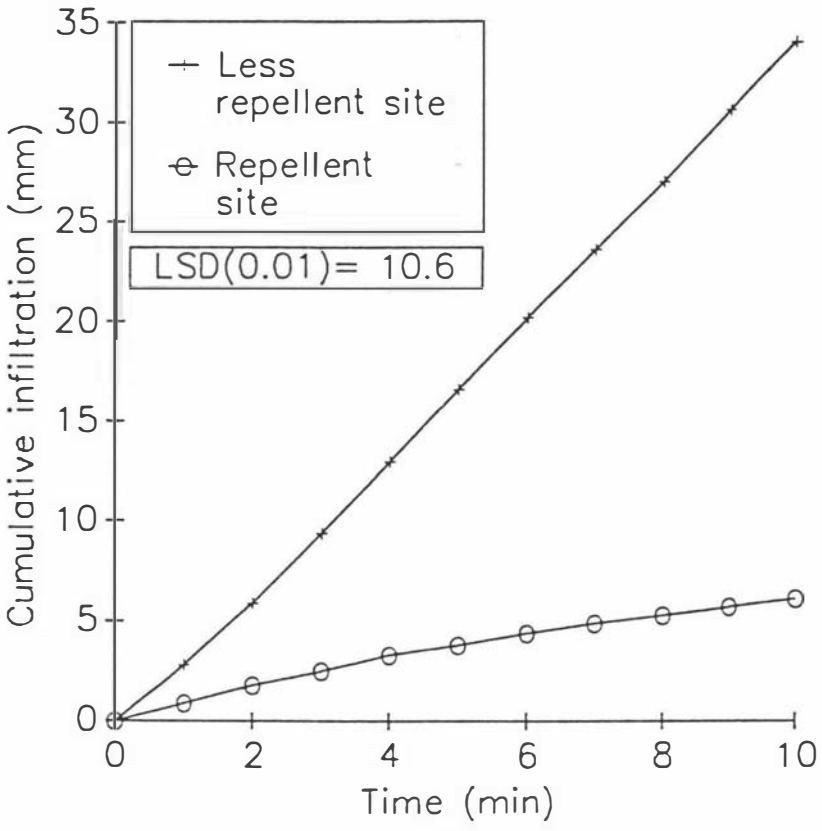


Figure 2.2. Mean water infiltration into repellent and less repellent Himatangi sand from a 10 mm positive head disc permeameter (3 replicates per site).

initial restriction in infiltration would produce substantial surface water redistribution during rainfall or irrigation. Travelling boom and big gun irrigators used in New Zealand agriculture commonly have application rates in excess of 100 mm h^{-1} (Cook 1983; John *et al.* 1985) and therefore much of the irrigation water would run off repellent areas. This has been observed at the experimental site where, immediately after irrigation, slightly elevated repellent areas remained dry while water ponded in lower areas.

Approximately linear relationships were found between cumulative infiltration, (I) and time, (t) for both the severely repellent and less repellent sites. Thus there were non-linear relationships between I and $t^{½}$. If cumulative infiltration is plotted against the square root of time the slope at short time when capillarity dominates infiltration is the soil sorptivity. Clothier *et al.* (1985) measured the saturated hydraulic conductivity and the matrix flux potential of the Himatangi sand. From these values the time over which sorptivity may be calculated (Philip 1969) is in the order of 10 seconds. This behaviour may be due to the water repellency of this soil. The ratio between ethanol and water sorptivity has recently been proposed as a field index of soil water repellency (Tillman *et al.* 1989).

Physical Techniques for Reducing Soil Water Repellency

Effect of soil water content on MED

An increase in gravimetric soil water content (w) from 0.03 to 0.05 caused a highly significant ($P < 0.01$) rise in soil water repellency (Fig. 2.3). The increased soil water content may have facilitated molecular conformational changes similar to those described in the physical abrasion experiment of this paper.

Above $w = 0.05$, soil water repellency declined rapidly to zero MED at $w = 0.08$. This means that the water repellent properties of the Himatangi sand are not expressed at gravimetric water contents above c. 0.08. As the soil dries below about $w = 0.08$, water repellency becomes severe. Field soil gravimetric water contents less than 0.08 have commonly been measured in summer. Using soil water diffusivity during horizontal

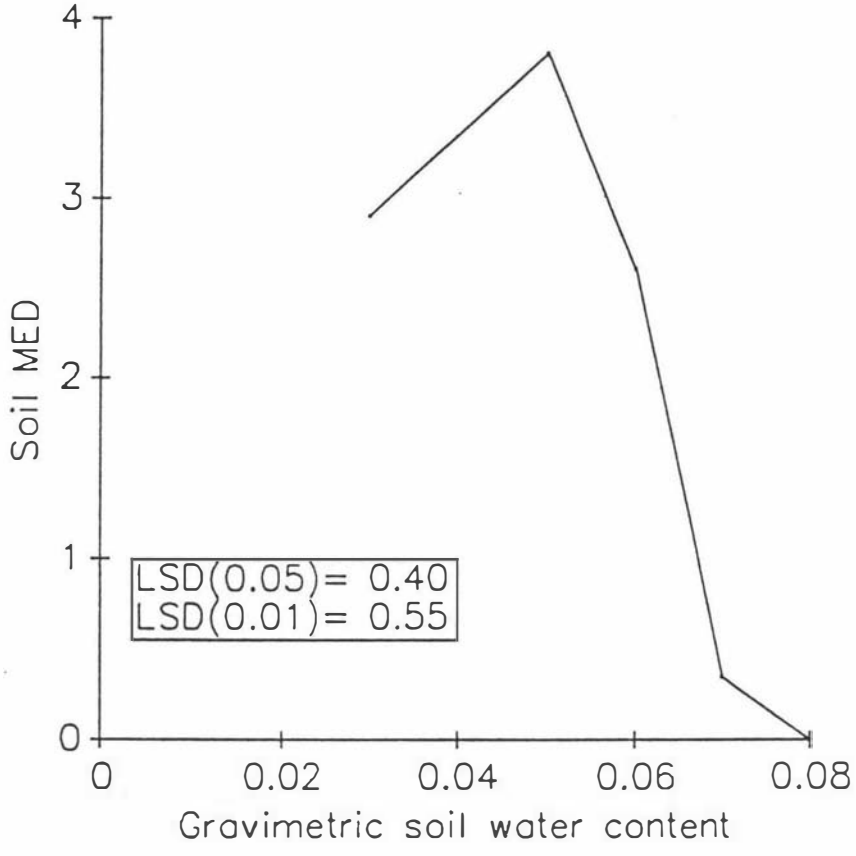


Figure 2.3. Water repellency (Molarity of Ethanol Droplet, MED) of the Himatangi sand at increasing gravimetric soil water contents.

absorption De Bano (1971) also found that the effect of water repellency was greatest when the soil was dry and decreased as the water content increased.

Effect of abrasion on MED

One hour of abrasion caused a highly significant ($P < 0.01$) reduction in soil water repellency (Table 2.1). An exponential decline occurred for up to 8 hours of shaking, after which further shaking did not significantly ($P > 0.05$) reduce MED. This is consistent with the observations of Ma'shum and Farmer (1985), who found that MED of a South Australian repellent soil declined from 2.3 to 1.1 after eight hours in a soil-water mixture (25g/100 cm^3). They separated the sand fraction to show that admixed discrete particulate organic matter was responsible for the maintenance of a residual MED of 0.9 for the whole soil after 16 hours of shaking.

Water repellency of the samples agitated for 2, 4, 8 and 12 hours significantly ($P < 0.01$) increased after standing for 72 hours. Ma'shum and Farmer (1985) reported reversible soil repellency when water repellent soil was freeze dried and then re-wet and oven-dried. They proposed that changes in the molecular conformation of the organic matter responsible for water repellency had occurred. We suggest that similar changes have occurred in this experiment. Abrasion may have caused a charge imbalance, which subsequent molecular conformational changes may have reduced to produce an increased number of hydrophobic groups exposed at the surface of discrete and sand grain-coating organic matter.

Shaking for 24 h was necessary to produce a relatively stable reduction in water repellency to an MED of 1.40. These observations suggest that cultivation, which will only cause soil disruption for a short period of time, may have a limited potential for reducing the water repellency of the Himatangi sand.

Table 2.1. Water repellency (Molarity of Ethanol Droplet, MED) of air-dry Himatangi sand immediately after agitation and at 72 hours after agitation commenced.

Agitation time (h)	MED	
	Immediate	At 72 h
0	2.65	2.65
1	2.00	2.10
2	1.55	1.80
4	1.45	1.70
8	1.30	1.50
12	1.40	1.70
24	1.35	1.30
48	1.40	1.30
Within series		
LSD(0.05)	0.16	0.18
LSD(0.01)	0.21	0.25
Between series		
LSD(0.05)	0.15	
LSD(0.01)	0.20	

CONCLUSIONS

The top 30 mm of Himatangi sand is severely water repellent at gravimetric water contents less than approximately 0.08. This soil condition reduces infiltration rates by an order of magnitude which restricts plant growth, particularly in the germination and establishment stages.

Abrasion was shown to reduce the water repellency of this soil. Although cultivation could be considered as a field treatment, the depth of the repellent horizon, the degree of repellency, and the somewhat reversible effect of abrasion may preclude cultivation as a viable field treatment option.

ACKNOWLEDGEMENTS

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2.2 A STUDY OF WATER REPELLENCY AND ITS AMELIORATION IN A YELLOW- BROWN SAND. 2. USE OF WETTING AGENTS AND THEIR INTERACTION WITH SOME ASPECTS OF IRRIGATION.

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Abstract

A range of soil wetting agents was evaluated in glasshouse experiments using the Himatangi sand. Comparisons of application rates required to overcome water repellency and enable ryegrass seedling emergence revealed significant differences ($P < 0.05$) in product performance. The dilution rate for wetting agent application was also found to be a significant ($P < 0.05$) factor for some products. In a field trial, pasture establishment was significantly improved on plots (4.8 x 10 m) which were band-sprayed with wetting agents (Wettasoil 12 l ha^{-1}, Aquagro 8 l ha^{-1}). Application rates were selected from the glasshouse experiments. However soil water content had a high spatial variability and did not differ significantly ($P > 0.05$) between plots. A blanket spray (20 l ha^{-1}) of Wettasoil on a cultivated area (45 m^2) of Himatangi sand increased the surface soil water content relative to untreated soil, however this effect was not maintained over the following months. Glasshouse experiments were conducted to study the relationship between some aspects of irrigation scheduling and the performance of wetting agents. Delays of up to 14 days in initial wetting following wetting agent application produced no significant ($P > 0.05$) effect on the ability of two wetting agents to increase soil infiltration. Shorter

irrigation return intervals consistently improved plant growth in untreated and wetting agent treated Himatangi sand.

INTRODUCTION

Wetting agents have been used successfully to overcome water repellency in turf culture and agriculture (Morgan *et al.* 1966; McGhie and Tipping 1983). Adding wetting agents to water lowers the surface tension of the solution, allowing initial infiltration. The amphiphilic wetting agent molecules are then adsorbed onto the repellent soil particles. This creates a more hydrophilic surface, and decreases the liquid-solid contact angle, enabling the infiltration of subsequent rain or irrigation water (Pelishek *et al.* 1962). Wetting agents have been found to enhance seed germination and establishment by improving soil moisture conditions in water repellent soils (Osborn *et al.* 1967; Osborn 1969). McGhie and Tipping (1983) developed a method for the use of wetting agents on a large scale. He adapted a boom to spray the chemical in bands behind a seed drill, thereby reducing chemical cost.

The effect of a high liquid-solid contact angle is reduced as the soil water content is increased (De Bano 1969b). Frequent, well managed irrigation could therefore be used to alleviate the effects of soil water repellency. The practical and economic viability of frequent irrigation may be restricted to intensive land uses, such as sports turf.

This paper reports the effects of wetting agent application and some aspects of irrigation management on the water repellency of the Himatangi sand. This yellow-brown sand, found on the west coast of the lower North Island, suffers from water repellency (Wallis *et al.* 1990a).

MATERIALS AND METHODS

Wetting Agent Experiments

Glasshouse evaluation of Aquagro, Wettasoil and Greenkeep

Seed trays were sown with 60 kg ha^{-1} *Lolium perenne* (var. Ellett) at 10 mm depth in air-dry Himatangi sand (MED = 2.6). The MED index is explained in Wallis *et al.* (1990a). The seed trays were then filled to the top with air-dry Himatangi sand. Wetting agents (Appendix) were applied to the bare soil surface using hypodermic syringes, at the range of application rates and dilutions listed in Table 2.2. Appropriate application rates were determined from previous experiments. The control received no wetting agent. Each treatment was replicated 3 times in a completely randomised design.

The seed trays were placed on trolleys in a glasshouse with the temperature controlled between 18 and 25°C. An overhead microjet irrigation system with a coefficient of uniformity (C_u) of 88.4% and application rate of 68 mm h^{-1} was used. The amount applied was matched to an average evaporation rate of 3 mm day^{-1} (July 1988). The return interval selected was 3.5 days. The grass was cut at a height of 15 mm using scissors, 15, 28, 41, 51 and 63 days after sowing.

Field blanket spray with Wettasoil

In March 1988, a paddock of Himatangi sand was prepared for sowing with glyphosate herbicide and rotary cultivation. In April 1988 two 45 m^2 plots on c. 10° slope were sown with a seed mixture comprising 20 kg ha^{-1} *Lolium perenne*, 6 kg ha^{-1} *Dactylis glomerata* and 4 kg ha^{-1} *Trifolium repens*. A knapsack sprayer was used in early May to blanket spray 20 l ha^{-1} Wettasoil at a 1:200 dilution on one plot.

The plots were irrigated with 45 mm of water (150 mm h^{-1}) immediately after the wetting agent application. Gravimetric soil water content to 50 mm depth was assessed before and after irrigation, with 5 samples removed per plot. The volumetric soil water content

of the plots to 200 mm depth was measured using a Time Domain Reflectometer (Topp *et al.* 1982 a,b) in May, July and August (10 measurements per plot).

Field band spray with Aquagro and Wettasoil

In March 1988, a paddock of Himatangi sand was prepared for over-sowing using glyphosate herbicide. A Duncan triple disc seeder was fitted with a boom sprayer, with the nozzles aligned directly behind the drill coulters to produce a band spray. The drill lines were 150 mm apart, with an average wetting agent band width of 30 mm. The treatments were applied to 4.8 x 10 m plots replicated four times in a completely randomised block design, as follows: Wettasoil at 60 l ha^{-1} in the band (12 l ha^{-1} overall), 1:100 dilution; Aquagro at 40 l ha^{-1} in the band (8 l ha^{-1} overall), 1:100 dilution. The control plots received no wetting agent. The seed mix used was as described previously.

Rainfall of 33 mm fell two days after the sowing/spraying operation. Volumetric soil water content from 0 to 200 mm was measured in the bands with 10 observations per plot before and after a 45 mm irrigation event in May 1988, and on subsequent dates in May, July and August using a Time Domain Reflectometer. Plant dry matter production was measured using triplicate 1 m^2 subsamples in May, July and August.

Interaction between irrigation and wetting agent performance

Effect of a delay in initial wetting

Seed trays were prepared to investigate the effect of delays in initial wetting following wetting agent application. The following wetting agent treatments were applied as explained previously: Wettasoil, 4 l ha^{-1}, 1:100 dilution; Aquagro, 30 l ha^{-1}, 1:100 dilution. The control received no wetting agent. Each treatment was randomly assigned to three blocks within each irrigation regime. The irrigation regimes were 0-, 7- and 14-day delays before initial irrigation. Overhead irrigation (C_u = 88.6%) was applied at 51 mm h^{-1} every 3.5 days to match an average evaporation rate of 5 mm day^{-1} (January 1989). Seed germination after 0, 7 and 14 days in air-dry Himatangi sand in the glasshouse was tested in a germination cabinet to ensure that the seed remained viable.

The grass was cut at a height of 15 mm using scissors, 15, 25, 36, 46 and 57 days after the first irrigation event for each irrigation regime.

Effect of irrigation return interval

Seed trays were prepared and the above wetting agent treatments applied. A treatment of air-dry Manawatu fine sandy loam (MED = 0) with no wetting agent was included. Each treatment was randomly assigned to three blocks in each of four trolleys. The trolleys were moved under the irrigation system on the appropriate days to give irrigation return intervals of 1, 7, 10 and 12 days. The irrigation system was set up as described above. The grass was cut at a height of 15 mm using scissors, 10, 21, 37, 50 and 69 days after the first irrigation event (all trolleys were first irrigated on the same day).

RESULTS

Wetting agent experiments

Glasshouse evaluation of Aquagro, Wettasoil and Greenkeep

Irrigation water applied to the seed trays was observed to infiltrate immediately in wetting-agent-treated soil. In the control soil water ponded to a depth of approximately 5 mm before running off from the seed tray edges. This may emulate field surface water redistribution in the Himatangi sand, where water may run off from drier, more water repellent areas to pond in lower- lying areas.

Plant growth in all wetting-agent-treated soil started significantly ($P < 0.05$) earlier and was significantly ($P < 0.05$) greater than the control (Table 2.2). Based on previous experiments relatively small increments between application rates for each wetting agent were selected; nevertheless, plant growth rates tended to be higher at higher application rates. Wettasoil was effective at application rates an order of magnitude lower than those of Greenkeep or Aquagro. Aquagro was effective at application rates approximately

Table 2.2. Growth rate of 'Ellet' ryegrass sown in seed trays of Himatangi sand and treated with the soil wetting agents 'Aquagro', 'Wettasoil' and 'Greenkeep' at a range of application rates and dilutions.

Chemical	Treatment Rate (l/ha)	Dilution	Ellet ryegrass growth rate (kg/ha per day) Days after sowing: 15	28	41	51	63
Aquagro	5	1:100	0.25	2.18	6.68	11.37	15.81
	20	1:100	0.20	2.34	6.73	10.04	17.48
	30	1:100	0.77	1.89	10.49	14.18	17.37
	10	1:500	0.04	0.41	3.94	7.99	15.78
	10	1:1000	0.04	0.84	7.32	12.45	17.11
Wettasoil	2	1:100	1.16	2.12	8.43	13.97	16.98
	4	1:100	1.57	2.18	10.25	12.83	16.13
	6	1:100	1.31	2.07	10.14	14.21	19.23
	8	1:100	1.34	3.08	11.60	15.50	20.28
	4	1:500	1.08	2.13	11.38	13.19	16.63
	4	1:1000	1.04	2.40	9.73	13.10	16.59
Greenkeep	40	1:100	0.06	2.01	5.03	8.83	13.41
	60	1:100	1.41	4.29	12.74	16.09	14.80
	80	1:100	1.25	3.13	12.09	15.84	15.57
	100	1:100	1.30	3.19	14.63	16.40	16.16
	60	1:250	0.83	3.35	15.20	16.25	16.78
	60	1:500	0.20	2.07	6.79	12.20	18.63
	60	1:1000	0.07	1.34	6.65	9.60	17.24
Control			0	0	0.38	2.29	8.25
LSD(0.05)			0.45	1.29	4.61	5.33	5.13
LSD(0.01)			2.03	1.73	6.17	7.13	6.5279

one-third those of Greenkeep. Wettasoil, Aquagro and Greenkeep have a similar cost per litre.

The effect of dilution rate varied with wetting agent. Low dilution rates (1:100, 1:250) significantly ($P < 0.05$) increased the effectiveness of Greenkeep up to 41 days after sowing. A low dilution rate causes a greater surface tension reduction in the wetting agent solution, enhancing infiltration into the water repellent soil. Plant growth 15 days after sowing was significantly ($P < 0.05$) greater at 1:100 Wettasoil dilution compared with 1:500 or 1:1000; however no significant difference was maintained after 15 days. Different Aquagro dilution rates produced no significant differences in plant growth.

Plant growth in the control soil increased with time after an initial delay. Frequent irrigation (return interval 3.5 days) would have slowly increased the surface soil water content until the critical gravimetric water content (approximately $w = 0.08$) enabled water to infiltrate to the seed at 10 mm depth.

Field blanket spray with Wettasoil

Field application of Wettasoil in a blanket spray (20 l ha^{-1}) produced a large increase in surface water content of repellent Himatangi sand (Table 2.3). Water run-off from the treated plot was visibly reduced. This observation and the water content data imply that the wetting agent treatment increased irrigation water infiltration. Although the 1988 Winter was particularly wet and 'field capacity' of the Himatangi sand has been observed in excess of 0.20 volumetric water content, the water content difference between the two plots was not maintained over the following 3 months.

Field band spray with Aquagro and Wettasoil

Field application of wetting agents in a band spray produced no significant ($P < 0.05$) improvement in surface soil water content within five months of sowing (Table 2.4). However the wetting agents did produce significantly ($P < 0.05$) greater plant growth after 3 months. The plant growth trend was consistent over the three sampling dates which spanned three months. Subsequent geostatistical surveys have

Table 2.3. Water content of the Himatangi sand following a blanket application of the soil wetting agent Wettasoil.

Treatment	Gravimetric water content to 50 mm (%)		Volumetric water content to 200 mm (%)			
	May before irrig.	May after irrig.	5 May 88	24 May 88	5 Jul 88	19 Aug 88
Wettasoil (20 l ha^{-1})	10.5 (1.6)*	33.1 (6.0)	14.8 (5.2)	18.5 (6.8)	16.3 (4.9)	21.1 (3.3)
Control	7.8 (5.2)	13.1 (4.2)	12.9 (5.4)	16.1 (6.2)	16.8 (4.5)	18.0 (3.4)

* Standard deviation

Table 2.4. Water content and pasture dry matter production of the Himatangi sand following band application of the soil wetting agents 'Wettasoil' and 'Aquagro'.

Observation date	Volumetric soil water content to 200 mm (%)				Pasture DM production (kg ha^{-1})			
	Wettasoil 12 l ha^{-1}	Aquagro 8 l ha^{-1}	Control	LSD (0.05)	Wettasoil 12 l ha^{-1}	Aquagro 8 l ha^{-1}	Control	LSD (0.05)
4 May 88 pre-irrig.	13.9	13.1	13.2	2.3	-	-	-	-
5 May 88 post-irrig.	24.4	22.9	22.6	3.0	-	-	-	-
24 May 88	19.1	17.6	17.8	2.4	24.6	30.3	7.4	27.6
5 Jul 88	21.3	18.7	18.6	2.8	211.1	194.4	81.0	79.3
19 Aug 88	28.5	26.7	26.3	2.1	947.7	1025.5	894.6	135.5

confirmed the high spatial variability of water content in the Himatangi sand (Wallis and Horne unpub. data). This may explain the non-significant water content differences found in this experiment.

Parr and Norman (1965) pointed out that the role of surfactants in biological systems may not be limited to merely a reduction in surface tension. The wetting agents may have increased plant growth by altering cell permeability, hence increasing nutrient uptake and by activating certain enzyme systems. Soil adsorption would decrease the biochemical activity of Aquagro and Wettasoil, however. Miller and Letey (1975) showed that Aquagro is strongly adsorbed.

Interaction between irrigation and wetting agent performance

Effect of a delay in initial wetting

A complex F' test (Le Clerg *et al.* 1962) revealed that a delay of initial wetting following wetting agent application caused no significant differences in plant growth at all dates after sowing. However if the initial wetting is delayed in the field, ultra-violet light degradation and physical displacement of wetting-agent-treated sand (e.g. by wind) may occur.

Effect of irrigation return interval

A complex F' test revealed that significant plant growth differences ($P < 0.05$) on days 10, 21 and 37 after sowing were produced by the selected irrigation return intervals (Table 2.5). A 1-day irrigation return interval produced significantly greater ($P < 0.05$) plant growth in the Manawatu soil up to 37 days after sowing. Plant growth in the water repellent Himatangi sand was significantly lower ($P < 0.05$) than that in the Manawatu soil for all sampling dates and irrigation treatments.

Plant growth in Wettasoil-treated soil was significantly greater ($P < 0.05$) at 1- and 7-day irrigation return intervals compared with 10- and 12-day return intervals. In the Aquagro treated soil no significant difference was observed at 10 days, however at 21 and 37 days

Table 2.5. Growth rate of 'Ellet' ryegrass sown in seed trays of Himatangi sand and Manawatu fine sandy loam, treated with the soil wetting agents Wettasoil and Aquagro, and irrigated with a range of irrigation return intervals (R.I.).

Soil	Treatment Chemical	R.I.(days)	Ellet ryegrass growth rate (kg ha^{-1} per day) Days after sowing: 10	21	37	50	69
Manawatu	-	1	2.61	9.88	9.56	10.88	12.09
		7	1.09	4.39	8.45	12.87	7.71
		10	0.69	4.64	6.48	9.92	9.20
		12	0.70	2.70	5.10	9.83	12.29
Himatangi	-	1	0	0	1.99	5.21	5.45
		7	0	0	0	0	0.32
		10	0	0	0	0	0
		12	0	0	0	0	0
Himatangi	Wettasoil 4 l ha^{-1}	1	1.59	5.51	6.15	6.49	6.01
		7	1.33	4.15	5.15	7.41	4.73
		10	0.43	1.37	1.93	4.91	6.12
		12	0.83	1.73	1.22	4.16	9.08
Himatangi	Aquagro 30 l ha^{-1}	1	0.35	6.02	7.50	7.62	6.70
		7	0	0.03	0.12	0.41	0.84
		10	0	1.12	0.94	2.92	4.92
		12	0.06	0.10	0.08	0.31	1.38
LSD (0.05)			0.68	2.53	2.36	3.07	3.16
Significance[A]			***	*	**	NS	NS

[A]Statistical significance of RI differences; * = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$; NS = not significant.

plant growth of the 1 day return interval treatment was significantly greater ($P < 0.05$) than for the 7, 10 and 12 day return intervals. Although the complex F' test revealed that the results for days 50 and 69 were not significant, there is some evidence of compensatory growth in the Manawatu soil and wetting- agent-treated Himatangi sand at 10- and 12-day return intervals.

Short irrigation return intervals consistently improved plant growth in untreated and wetting-agent-treated Himatangi sand. Short return intervals would have facilitated water infiltration by the maintenance of higher surface soil water contents.

CONCLUSIONS

Wetting agents are capable of improving the surface soil water content and plant growth in water repellent Himatangi sand. The application rate required is dependent upon the product used, and the dilution rate for application may also affect wetting agent performance. Glasshouse experimentation can improve wetting agent selection and application decisions, however in the field other factors such as application method, cultivation and irrigation management may affect wetting agent performance. The effective life of wetting agents in the field also needs further evaluation.

Wetting agent performance was not affected by a delay in initial wetting following application to the Himatangi sand in the glasshouse. However, in the field other factors such as ultra-violet light degradation and soil displacement by wind may reduce the effectiveness of wetting agents if initial wetting does not closely follow chemical application.

Short irrigation return intervals improved plant growth in both untreated and wetting agent treated Himatangi sand. Short return intervals are often impractical and uneconomic in agriculture, but may represent a viable treatment option for intensive horticultural enterprises.

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APPENDIX. Wetting agents used in field and laboratory experiments.

Trade Name	Chemical Description	N.Z. Supplier
Wettasoil	Nonionic surfactant; a blend of polypropylene glycol and nonyl phenol ethoxylates	Wrightson Turf
Aquagro	Nonionic surfactant comprising 50% polyoxyethylene ester and 50% polyoxyethylene ether	Bell Booth Group Ltd
Greenkeep	Nonionic surfactant; an ethylene oxide derivative	ICI*

*NOTE: ICI have discontinued marketing this product in New Zealand

CHAPTER THREE: SPATIAL AND TEMPORAL VARIABILITY OF SOIL WATER REPELLENCY

3.0 INTRODUCTION

The spatial and temporal variability of soil water repellency are characteristics that have been noted since the earliest research but have attracted inconsequential quantitative work. Indeed, such variability has often made the study of soil water repellency difficult (Bond 1972; Tucker *et al.* 1990; Wallis *et al.* 1990a). In this chapter geostatistics, a modern technique for quantifying spatial variability, is described and used to evaluate the variability of soil water content in the Himatangi sand.

3.01 Spatial and Temporal Variability of Repellency

Jamison (1945) was the first to find that soil water contents can vary widely over short distances in repellent soils. He determined soil moisture content on a 3-dimensional grid to derive cross-sections of repellency in a Florida citrus orchard. He noted that rain or irrigation water moved through the soil in a non-uniform manner and often bypassed large volumes of dry soil, following 'channels of lower resistance to wetting'. Jamison concluded that high replication was necessary when sampling repellent soil. Bond (1964) used a rhodamine dye to trace water movement under ring infiltrometers and after rain on repellent South Australian sands. He found that infiltration from the infiltrometers and from rainfall was non-uniform, and soil moisture content varied from 1 - 8% over a distance of 10 mm. Hendrickx *et al.* (1988a,b) used soil water content measurements, the WDPT index, iodide and bromide tracers to compare water movement in repellent and nonrepellent soil. The topsoil of the nonrepellent sand wetted uniformly, while the repellent topsoil generated preferential flow pathways which extended into the subsoil.

Seasonal changes in repellency have been recognised for many years (e.g. Jamison 1945). Holzhey (1969) pointed out that the intensity and seasonal persistence of repellency is linked to the prevailing climate, which has both a direct effect and an indirect effect *via*

plant community composition. The direct effect of the climate is the effect of the seasonal balance between rainfall and evaporation upon the soil moisture deficit. Repellency is most strongly expressed when the soil is dry (e.g. DeBano 1971; Wallis *et al.* 1990a).

3.02 Geostatistics

The use of geostatistics in soil science has increased rapidly in recent years as a technique for quantifying the spatial variability of soil properties. Geostatistics may also be used to study the temporal variability of spatially dependent soil properties.

Classical statistics assumes that the mean of a selected soil property value is the expected value everywhere in the unit, with an estimation error expressed by the within-unit variance. This approach assumes that variability about the mean is random and contains no reference to the geographical distribution of differences within the sampling units. Geostatistics accounts for both the structured and random characteristics of spatially (or temporally) distributed variables to provide quantitative tools for their description and optimal, unbiased estimation (Trangmar *et al.* 1985).

3.021 Geostatistics Theory

Geostatistics is largely the application of regionalised variable theory, developed by Matheron (1965) from Krige's (1951, 1960) empirical ideas that the spatial estimation of gold content in ore bodies could be improved by taking the degree of similarity, or autocorrelation, between adjacent samples into consideration.

The theory requires certain assumptions regarding stationarity of the mean and variance of a soil property, so that the structure of the variation can be regarded as constant within a given region. If the spatial autocorrelation coefficient, $\rho(\mathbf{h})$,is used, full second-order stationarity, i.e. of the mean and variance, is assumed:

$$\rho(\mathbf{h}) = \frac{E[z(x) \cdot z(x+\mathbf{h})] - \mu^2}{[z(x) - \mu]^2} = \frac{C(\mathbf{h})}{C(0)} \quad (1)$$

where E is the expectation, μ is the mean, $z(x)$ and $z(x+h)$ are the values of a property z at x and $x+h$ separated by the lag vector **h**. $C(\mathbf{h})$ is the covariance of the property at lag **h** and $C(0)$ is the covariance at lag $\mathbf{h} = 0$, which is equivalent to the variance of z under the conditions of second-order stationarity.

Because estimates of the variance tend to vary without limit as the size of the area is increased, Matheron (1971) proposed the weaker assumptions of the *Intrinsic Hypothesis*, namely stationarity of the mean and of the variance of the *differences* between samples a given distance apart. This requires no assumption about the variance of z. The semivariogram function $\gamma(\mathbf{h})$ is then the measure of spatial variation:

$$\gamma(h) = 1/2 \; E[z(x) - z(x+\mathbf{h})]^2 \quad (2)$$

Under full second-order stationarity the semivariogram and the autocorrelation coefficient are equivalent tools:

$$\gamma(\mathbf{h}) = C(0)[1 - \rho(\mathbf{h})] \quad (3)$$

The semivariogram has more general applicability than the autocorrelation coefficient and therefore is particularly useful for reconnaissance. Estimates of the semivariogram can indicate the presence of local or global drift or trend, which means that the *Intrinsic Hypothesis* does not hold. Drift should be removed before further analysis and the semivariogram estimated from the residuals (Oliver 1987). Semivariogram analysis has the added advantage of defining parameters needed for interpolation by kriging (Trangmar *et al.* 1985).

3.022 The Semivariogram

The semivariogram can be estimated without bias from sample data in 1,2 or 3 dimensions and describes the spatially dependent component of the random function Z:

$$\gamma(\mathbf{h}) = 1/2\, M(\mathbf{h}) \sum_{i=1}^{M(\mathbf{h})} [Z(x_i) - Z(x_i+\mathbf{h})]^2 \qquad (4)$$

where $M(\mathbf{h})$ is the number of comparisons at lag **h** and $Z(x_i)$ and $Z(x_i+h)$ are the values of the variable at any two places separated by the lag vector **h**.

Missing data are allowed for by including only the actual number of comparisons at any given lag (Webster 1985). The semivariogram can be estimated in different directions to detect anisotropy in the variation (Trangmar *et al.* 1985).

The semivariogram represents the average rate of change of a property with distance and its pattern, scale and general form describes the pattern of spatial variation (Trangmar *et al.* 1985). Webster (1982) described the characteristic one-dimensional forms of the semivariogram (fig. 3.1).

General — The steepness of the initial slope indicates the intensity of change in a property with distance and the rate of decrease in spatial dependence.

Fig 3.1a — The parabolic shape near the origin represents continuous variation with local drift. Thus the mean changes over short distances and the *Intrinsic Hypothesis* does not hold.

Fig 3.1b — This semivariogram indicates continuous variation that is unbounded; therefore the data are not second-order stationary because the mean is changing with distance.

Fig 3.1c, Fig 3.1d — A positive y-axis intercept is termed 'nugget variance' and includes the variation unresolved by the sampling interval,

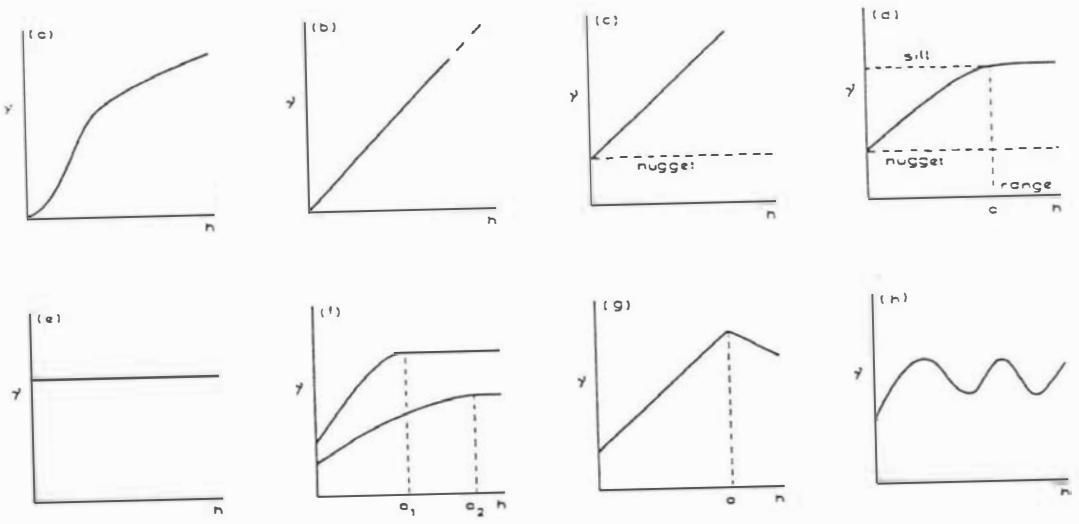


Figure 3.1. Examples of semivariogram forms (after Oliver 1987).

variation due to measurement error and any purely random variation. A large nugget variance in a raw semivariogram obscures any drift.

Fig 3.1d, Fig 3.1f — The structured element of the semivariogram reaches a maximum and flattens. This maximum is the 'sill variance' which indicates that, at the scale implied, the data are second-order stationary. The lag at which the sill is reached is called the range, i.e. the limit of spatial dependence.

Fig 3.1e — The semivariogram is pure nugget, indicating no spatial dependence in the data at the scale sampled. Thus sampling would need to be more intensive to reveal any structure in the variation.

Fig 3.1g — The 'hole effect' semivariogram suggests repetition in the data that is not strictly periodic. The slope reversal is rarely marked in practice, suggesting repetition at an irregular spacing.

Fig 3.1h — This semivariogram represents a further development of Fig 3.1g, i.e. periodic variation.

3.023 Sampling Strategies

Most authors (e.g. McBratney *et al.* 1981) advocate a preliminary survey to determine lag sizes and directions. As a rough guide, a minimum of 10 lags with 10 pairs of points in each direction is desirable (Bramley and White 1991b). Oliver (1987) recommended a minimum of 100 comparisons at the first lag, however Taylor and Burrough (1986) suggested that this can be refined relative to the requirements of the study and the nature of the spatial variation once this has been defined.

The most commonly used sampling pattern is the square grid. Nested sampling, i.e. a grid within a grid, is becoming increasingly popular since it allows for a greater number of lags to be tested within a given area (Bramley and White 1991b) and may allow

considerable economy in sampling effort without any significant loss of semivariogram precision (Oliver and Webster 1987).

3.024 Modelling the semivariogram

McBratney and Webster (1986) discussed fitting appropriate models to the experimental values of $\gamma(\mathbf{h})$ in detail. Suitable models must be able to incorporate the main semivariogram features described above, be conditional negative semi-definite functions and in two dimensions must be capable of incorporating anisotropy.

Linear, spherical and exponential models are permissible functions for semivariograms and will describe most. However many semivariograms are represented by combinations of models; for instance most have nugget variance and therefore the model can be regarded as nested (Webster 1985).

i The linear model

The linear model takes the form:

$$\gamma(\mathbf{h}) = C_o + k(\mathbf{h}); \quad \mathbf{h} > 0 \qquad (5)$$

where C_o is the nugget variance and k is the slope. Note that this model has no sill, and therefore no range (e.g. Fig. 3.1c). In the case where $k = 0$ (e.g. Fig. 3.1e), the variogram is said to show a pure nugget effect (Webster 1985); that is, there is no spatial dependence at the scale of sampling.

ii The spherical model

The spherical model takes the form:

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$$\hat{\gamma}(\mathbf{h}) = C_o+C[1.5\mathbf{h}/a]-[(h/a)^3/2]\ ;\ 0<\mathbf{h}<a$$
$$\hat{\gamma}(\mathbf{h}) = C_o+C;\ \mathbf{h}>a \qquad (6)$$

Its tangent at $\mathbf{h} = 0$ cuts the sill at $2a/3$ (Fig 3.2), where a is the range, $\mathbf{h}$ the lag, C_o the nugget variance and C_o+C the sill variance. In theory the spherical model is three-dimensional, although Webster (1985) noted that it nearly always fits experimental results from soil sampling better than a one-dimensional or two-dimensional analog, such as the circular model (which is not recommended for describing semivariograms).

iii The exponential model

The exponential model takes the form:

$$\hat{\gamma}(\mathbf{h}) = C_o+C[1-\exp(-\mathbf{h}/r]\ ;\ \mathbf{h}>0 \qquad (7)$$

Here, r is a distance parameter which controls the spatial extent of the function (Webster 1985). In the exponential model, $\gamma(\mathbf{h})$ approaches the sill asymptotically and there is no definable range. However, since the semivariance must cease to increase beyond a certain point, the range is taken to be equal to $3r$, where $\gamma(\mathbf{h})$ is approximately equal to C_o + $0.95C$ (Webster 1985). This approach may overestimate the range (Oliver and Webster 1987), in which case the spherical model would probably give a better fit because it curves more tightly.

3.025 Selection and Fitting of Semivariogram Models

Selection of the best model is normally by a simple comparison of the residual sum of squares after fitting each model to the data. When the models being compared estimate an unequal number of parameters, the Akaike Information Criterion (AIC) may also be calculated (McBratney and Webster 1986):

$$AIC = n[\ln(R)] + 2p \qquad (8)$$

where n is the number of semivariance observations, p is the number of estimated

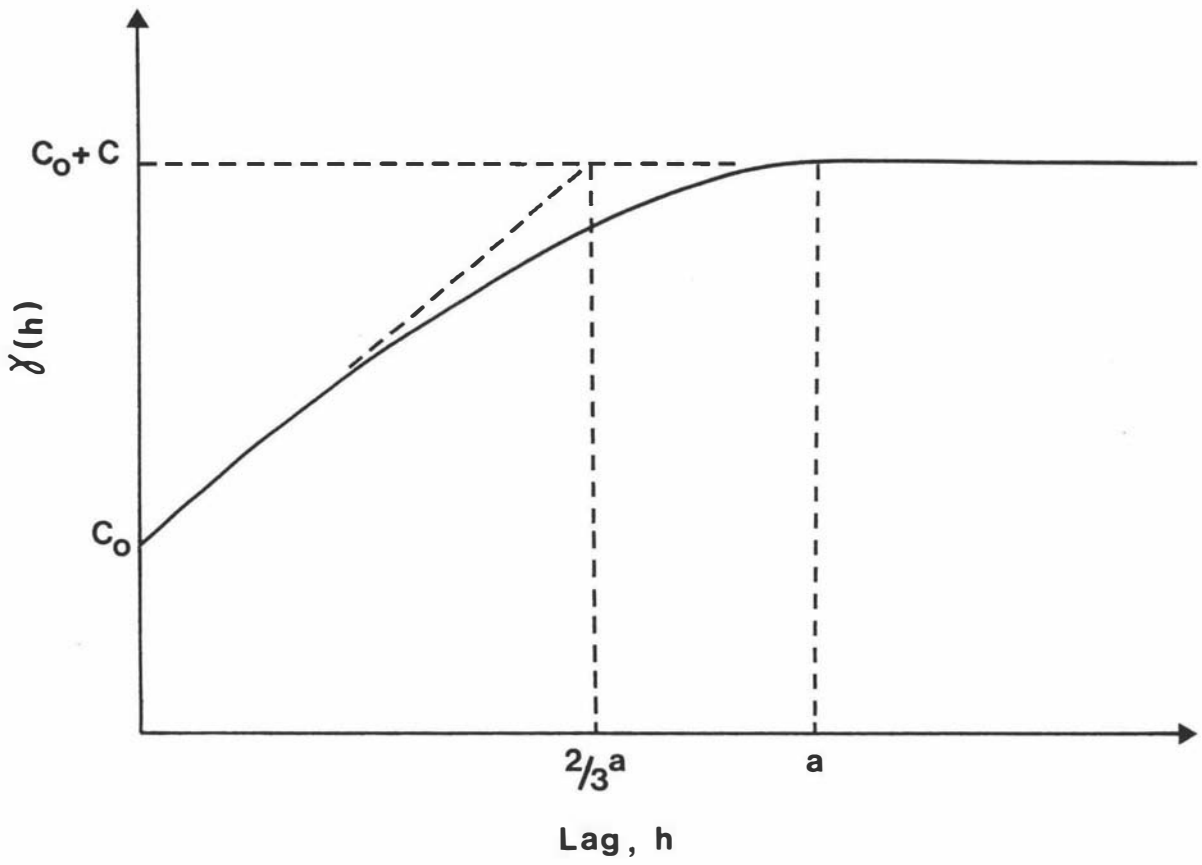


Figure 3.2. A spherical semivariogram model, identifying the range, *a*, the nugget variance, C_o and the sill variance at $C_o + C$ (after Trangmar *et al.* 1985).

parameters and R is the residual sum of squares of deviation from the fitted model. The model with the smallest AIC value is the best.

The method of fitting the model to the semivariogram must also be considered. The standard method of least-squares fitting gives equal weighting to each semivariance observation, regardless of the number of sample pairs used for their generation (Armstrong 1984). Therefore the method of weighted least-squares is recommended unless an equal number of sample pairs is used at each lag (Cressie 1985).

3.026 Applications of Geostatistics

The applications of geostatistics in soil science include:

1. Generation of a convenient summary of soil variability in the form of a semivariogram, which may act as a stimulus to more detailed modelling (Laslett *et al.* 1987);

2. The form of the semivariogram raw data and/or model can suggest underlying mechanisms responsible for the spatial variation observed and indicate other methods suitable for further investigation and mapping (Oliver 1987);

3. The design of optimal sampling schemes (McBratney *et al.* 1981);

4. Interpolation of variables at unsampled locations, first used for gold exploration in South Africa and called 'kriging' (Krige 1951, 1960; Journel and Huijbregts 1978);

5. Determination of the spatial interdependency between variables (e.g. Russo 1984; Davidoff and Selim 1988).

3.027 Limitations of Geostatistics

When interpreting semivariograms the following points should be borne in mind:

1 The form of the semivariogram, especially the range, is a function of the scale of investigation. The variability of a soil property may occur over a range of different scales, which may change by orders of magnitude, such that each scale of observation integrates the variabilities apparent at smaller scales (Oliver and Webster 1986). The ratio of the smallest to the largest lag should be made as small as possible (Laslett *et al.* 1987; Bramley and White 1991b).

2 The semivariogram is also dependent upon the 'support' of the sample, i.e. its size, shape and orientation. The larger the sample volume, the more variation it contains relative to that between samples, which has a smoothing effect on the variation. The support should therefore remain constant throughout an investigation.

3 The precision of the semivariogram is dependent upon the number of comparisons at each lag, the sampling interval and the intensity of spatial variation. The number of sampling points should be as large as possible.

4 Changing drift may have an effect on the semivariogram and considerably reduce its value. The problems of changing drift are complex, and comprehensively dealt with by Webster (1985).

5 There is no means of statistically testing semivariograms for anisotropy (Laslett *et al.* 1987). Currently, semivariograms representing a range of orientations are either compared by eye or with an 'anisotropy ratio' calculated over the first few lags where the semivariogram is approximately linear (e.g. Trangmar *et al.* 1985). The problem of developing a statistical test for anisotropy is compounded by the fact that the requirement for weighted least-squares prevents a conventional covariance analysis of grouped data (Bramley and White 1989b).

3.03 The Time Domain Reflectometer

Soil water content was measured using a Soil Moisture Corporation Time Domain Reflectometer (TDR) (fig. 3.3). The TDR measures the propagation velocity of electromagnetic waves through the soil medium,which is dependent upon the dielectric constant or relative permittivity, k_a of the medium through which it travels. The dielectric constant is the ratio of the capacitance of a capacitor with a specified medium (dielectric) between the plates to the capacitance of the same capacitor in a vacuum. As the soil moisture increases, k_a increases and the propagation velocity of the electromagnetic wave decreases.

Topp et al. (1980a,b; 1984) found that the apparent dielectric constant was primarily a function of volumetric water content, θ and was nearly independent of soil texture, density, temperature and soluble salt content. The TDR provided an integral measurement of soil moisture content over the length of the probes used (Topp *et al.* 1982a,b). Topp *et al.* (1984) showed that TDR measurements of soil water content in the field were as accurate and precise as those from gravimetric determinations (accuracy $\pm$ 0.02 m^3 m^{-3} (standard deviation), precision $\pm$ 0.01 m^3 m^{-3}).

The sample volume of the TDR is an important parameter for geostatistical analysis. Baker and Lascano (1989) assessed the spatial sensitivity of the TDR using probes of 3.175 mm diameter and 300 mm length, and produced the relative sensitivity distribution depicted in figure 3.4. Soil moisture measurement was largely confined to a quasi-rectangular area (20 x 65 mm) surrounding the probes, with no significant variation in sensitivity along the probe length. Some influence extended to an area of approximately 60 x 80 mm, and sensitivity was not uniform within the region of soil influencing the measurement. Baker and Lascano (1989) pointed out that an ideal sensor of soil moisture should have a relative sensitivity of unity throughout its given region of influence and a relative sensitivity of zero everywhere else. They further noted that the 'ideal sensor' would be particularly important if soil moisture is distributed heterogeneously within the region of influence.

The TDR technique has gained popularity in recent years for soil water content



Figure 3.3. Use of the time domain reflectometer for a geostatistical analysis of soil water content in the Himatangi sand (photo M.G. Wallis).

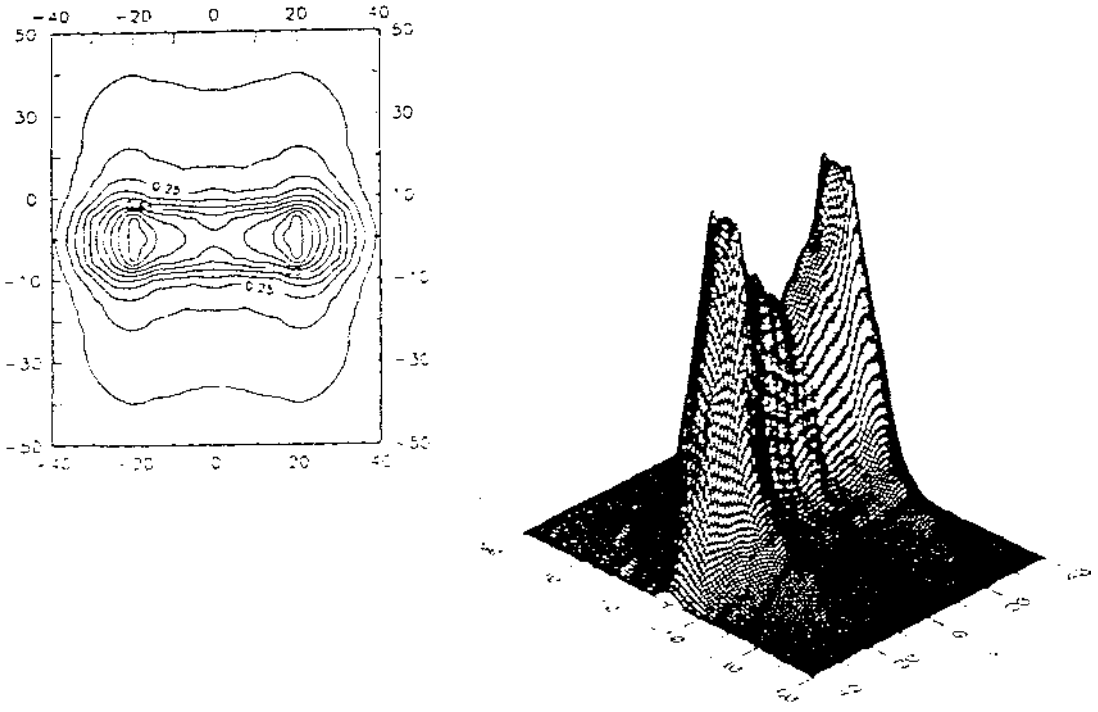


Figure 3.4. Two-dimensional representation of TDR sensitivity with water as the continuous medium. Both contour and surface plots are shown. Values at each point in the x-y plane represent the product of the transverse and normal relative sensitivities (after Baker and Lascano 1989).

measurement (Baker and Lascano 1989). The technology has been evaluated comprehensively, and has numerous advantages over other techniques. The TDR provides accurate, rapid and nondestructive assessment of θ (Campbell and Mulla 1990). The 'universal equation' of Topp *et al.* (1980a,b) provides a relationship between the apparent dielectric constant and θ for all soils, eliminating the need for individual soil calibration. The TDR can discriminate accurately between frozen and unfrozen water content (Patterson and Smith 1981; Stein and Kane 1983) and can permit simultaneous determination of soil water content and soil salinity (Dalton *et al.* 1984; Topp *et al.* 1988). Soil salinity is calculated from the soil electrical conductivity, which affects the electromagnetic wave attenuation.

Compared to neutron moderation techniques, the TDR poses no radiation hazard and may be used for θ measurement close to the soil surface. Baker and Lascano (1989) pointed out that horizontal probe installation should be possible to within 20 mm of the soil surface with little loss in accuracy. The sample volume of the TDR is more well defined than with neutron moderation, in which the soil sampled is a sphere of diameter *c.* 150 mm in wet soil and *c.* 700 mm in dry soil (Van Bavel *et al.* 1956). TDR probes are less expensive and easier to install than neutron access tubes, and the probes may be pushed into many soils rapidly by hand, avoiding the necessity for a large number of *in situ* probes.

The TDR technique has some limitations. Probes inserted vertically have poor depth resolution of soil moisture content (Campbell and Mulla 1990), however changing the probe diameter along the length of the probes can be used to create electrical discontinuities and determine the soil moisture content at particular depth increments (Topp and Davis 1985). TDR moisture content measurement is also restricted with very short probes in dry soil, when the electromagnetic wave travel time becomes very short and the dielectric constants of soil minerals dominate the apparent dielectric constant (Zegelin and White 1989). Dalton and van Genuchten (1986) cited the practical lower limit of probe length as 0.1 m.

Because the TDR sensitivity is concentrated in the immediate vicinity of the probes (Baker

and Lascano 1989) and the dielectric constant of air is much lower than that of moist soil, errors may be generated by soil disruption in this zone. Annan (1977) and Topp (1987) noted that air gaps caused by shrinking and swelling soils, frost heave, rodent burrows and cracking between the probes appeared to be the most serious sources of error. Horizontal TDR probe emplacement from a backfilled soil ditch may introduce error due to soil disturbance (Leary 1988). Errors may also be induced if the probes wobble as they are inserted (Baker and Lascano 1989). This problem may be minimized by installation of the probes at an angle (Topp *et al.* 1980; Topp and Davis 1985).

3.1 A GEOSTATISTICAL ANALYSIS OF WATER CONTENT SPATIAL VARIABILITY IN A REPELLENT SOIL UNDER IRRIGATED DAIRY PASTURE.

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Abstract

The volumetric water content (θ) of the Himatangi sand from 0 - 200 mm depth was measured with a time domain reflectometer on two adjacent sites, A and B, each c. 860 m^2. A nested grid sampling strategy produced a high number of sample pairs for estimates of the semivariance; however bias in the semivariance and sample variance estimates appeared to result from the concentration of the nested sites within the main grid. θ varied isotropically and generally followed a normal distribution. Variograms of θ changed over time and were not transferable between the two sites, although there was evidence of drift in the mean at site B. There was no consistent seasonal pattern of spatial variability; however the coefficient of variation (C.V.) of θ exceeded 30 % on 6 sampling dates in summer (November to March) compared to a C.V.(θ) = 6.6% in October. The range, a of spatial dependence in θ at site A was 8 - 10 m in summer and 15 m in October. At site B, linear variograms were produced with no definable range.

An application of 45 mm irrigation with a travelling-boom irrigator to site A markedly increased the nugget and sill variance, increased C.V.(θ) from 32.3 to 34.6 %, decreased a slightly from 9 to 8 m and increased the soil water content by 18 mm. Irrigation of site B also greatly increased the nugget variance, increased C.V.(θ) from 49.9 to 53.2 % and decreased the soil water content by 9.6 mm. When 100 l ha^{-1} of a soil wetting agent was applied prior to irrigation of site A the increase in nugget and sill variance was reduced, C.V.(θ) decreased from 30.4 to 16 %, a increased from 8 to 15 m and the soil water content increased by 29.4 mm.

Introduction

Water repellent soils exhibit hydrophobic properties when dry so that infiltration into the soil matrix is reduced (Brandt 1969b). The Himatangi sand is a yellow-brown sand (Aquic Udipsamment) that is found on the west coast of the lower North Island, New Zealand (Cowie *et al.* 1967; Cowie 1968) and is severely repellent when dry (Wallis *et al.* 1990a). Wallis *et al.* (1991) found that repellency of dry Himatangi sand reduced the infiltration rate to c. 1 % of the 'potential' infiltration rate if the soil were nonrepellent. Wallis *et al.* (1990b) found that repellency of the Himatangi sand reduced plant establisment and growth. Field studies were very difficult because of the extreme spatial variability of soil water content.

High spatial variability of soil moisture content appears to be a characteristic property of repellent soils. Bond (1964) found that the moisture content within a repellent soil after rainfall varied from 1 to 8 % over 10 mm distance. A number of studies have found that rain or irrigation water penetrates repellent soils through channels and leaves the remainder of the soil dry (Jamison 1945; Bond 1964; Gilmour 1968; Hendrickx *et al.* 1988a). Hendrickx *et al.* (1988a) found that the channels were initiated at surface locations where repellency was least. The channels effectively created preferential flow pathways for water and solute movement which extended into the subsoil.

Details of the cause(s) of high spatial variability of repellency are unknown, but are most likely determined by the nature of the organic coatings of soil particles, which in turn is related to the nature and distribution of past and/or present vegetation species (e.g. Adams *et al.* 1969; Roberts and Carbon 1972; McGhie and Posner 1980, 1981) and microbial populations (Bond and Harris 1964; Bornemisza 1964; Savage *et al.* 1969b). Bond (1964) suggested that repellency may be related to both plants and associated microorganisms. Micro-scale variability of soil water content in repellent soil (over a few mm or cm) may also be due to microtopographic, physical and chemical variability of the soil (Bond 1972; Mallik and Rahman 1985).

Little is known about the effect of soil wetting agents upon the spatial variability of

repellency. Soil wetting agents are surfactant chemicals which lower the liquid surface tension and solid-liquid contact angle, increasing infiltration into repellent soil (Pelishek *et al.* 1962). Wetting agents have been widely used in sports turf and, to a lesser extent in agriculture (Wallis *et al.* 1989; McGhie 1983). Sawada *et al.* (1989) used computer-assisted tomography applied to gamma-ray attenuation measurements to measure the distribution of water in sections of soil following infiltration with and without applications of wetting agents. They found that effective wetting agents improved the wetting uniformity of repellent soil. The effect of soil wetting agents upon wetting uniformity have not been quantified at field-scale.

Geostatistics is a technique which may be used to measure both the structured and random characteristics of spatially distributed variables. Trangmar *et al.* (1985) provided one of several comprehensive reviews on the subject. The use of geostatistics in soil science has increased rapidly in recent years to describe the spatial distribution of soil properties and to provide optimal, unbiased estimation of the properties at unsampled locations (the process of kriging) (e.g. McBratney *et al.* 1981; Oliver and Webster 1987).

The objective of this series of experiments was to determine the effect of repellency upon infiltration by measuring the spatial variability of water content in repellent Himatangi sand:

(a) At different times of the year;
(b) Before and after irrigation;
(c) Before and after irrigation and wetting agent application.

Methods

A time domain reflectometer (TDR) (Topp and Davis 1985) was used to measure the volumetric water content (θ) from 0 - 200 mm depth on two areas each c. 860 m^2 (sites A and B) of Himatangi sand on a dairy farm located 1.2 km east-south-east of Himatangi (NZMS 260 S24/073869). The pasture sward comprised predominantly *Lolium perenne* and *Trifolium repens* sown in Autumn 1988 and a widespread population of *Trifolium subterraneum* and *Agrostis* spp. The two sites (A and B) were 1 m apart on similar

topography. Each site comprised a main and nested grid (i.e. a grid within a grid) which allowed for a greater number of sample separation distances (lags) to be tested within a given area (Bramley and White 1991b). The minimum lag of 150 mm was selected on the basis of the sample support (Webster 1985); i.e. the spatial extent of the TDR θ measurement. Baker and Lascano (1989) found that the TDR measured a quasi-rectangular area of 60 x 80 mm around the probes. The nested grid within each main grid comprised 15 x 15 nodes orientated north-south (N-S) and east-west (E-W) at 150 mm spacing (2.1 m x 2.1 m overall) and was located immediately south-east of the main grid centre. The main grids comprised 15 x 15 nodes orientated N-S, E-W with 2.1 m spacing (29.4 m x 29.4 m overall). The 15 x 15 grid patterns were determined primarily by the time constraints of sampling.

Sampling was conducted on a range of dates (table 3.1). The dates 31/01/89 and 01/02/89 represent sampling before and after 45 mm irrigation with a travelling boom irrigator. The irrigator had an application rate of c. 135 mm h^{-1} and a Christiansen's coefficient of uniformity, C_u = 89 %. The application rate exceeded the infiltration rate of dry, repellent soil but was less than the infiltration rate of moist, nonrepellent soil (Wallis *et al.* 1990a). The dates 16/11/89 and 17/11/89 represent sampling of sites A and B before and after a similar irrigation event when 100 l ha^{-1} of the soil wetting agent 'Wettasoil' was applied to site A with knapsack sprayers within 1 h before irrigation. The high Wettasoil application rate was used to ensure its effectiveness in alleviating the soil's repellency (Wallis *et al.* 1990b).

The depth to the water table from the soil surface was monitored with four piezometers placed at 3 m spacing along the west side of the main grid.

Prior to geostatistical analysis the frequency distribution of each data set was analysed to evaluate whether log transformation was necessary. The untransformed and log transformed data was processed with Statistical Analysis Service (SAS) computer programmes and the probability of normality tested with the Kolomogorov *D* statistic (Shapiro *et al.* 1968).

The semivariance $\gamma(\mathbf{h})$ was estimated by $\hat{\gamma}(\mathbf{h})$ for θ at each sampling date using the

equation (e.g. Trangmar *et al.* 1985):

$$\hat{\gamma}(\mathbf{h}) = [1/2m(\mathbf{h})] \sum [\theta(x_i) - \theta(x_i + \mathbf{h})]^2 \quad (9)$$

where $m(\mathbf{h})$ is the number of pairs of θ observations separated by lag $\mathbf{h}$, $\theta(x_i)$ and $\theta(x_i + \mathbf{h})$ represent the value of θ at two positions separated by lag $\mathbf{h}$, and x_i denotes a pair of cartesian coordinates with $i = 1,2,3 \cdots n$.

Values of $\hat{\gamma}(\mathbf{h})$ were calculated in the N-S and E-W directions of the sampling grid to enable a visual evaluation of each data set for isotropy. Following assumption of isotropy, values of $\hat{\gamma}(\mathbf{h})$ were then calculated for all directions (360°), grouped into lag classes of the smallest separation distance for each grid (i.e. 0.15 and 2.1 m, table 3.2) using the smoothing technique of Webster (1985), and variograms ($\hat{\gamma}(\mathbf{h})$ *vs* $\mathbf{h}$) were plotted. The smoothed variograms were fitted by weighted-least squares optimisation with linear, spherical and exponential models (e.g. Webster 1985) using weights for the number of pairs of observations in each lag class.

Results and Discussion

Data frequency distribution

The D test has similarities to the t test but tests the frequency distribution against the null hypothesis of a normal function. For data sets exceeding 40 observations ($n > 40$) the approximate critical D value at the 5 % level of probability is given by the equation (Shapiro *et al.* 1968):

$$D_{(0.05)} \approx \frac{1.3581}{\sqrt{n}} \quad (10)$$

The sampling strategy produced $n = 450$ (2 x 15 x 15, including 4 samples at the corners of the nested grid coincident with main grid nodes). Therefore the approximate critical $D_{(0.05)}$ was 0.064. For all untransformed θ data sets, the D statistic exceeded 0.064 (table 3.1), so that the probability that the distributions were not normal exceeded 5%.

Table 3.1. Summary of results for the frequency distribution analysis of volumetric water content, θ (0 - 200 mm depth) in repellent Himatangi sand.

Analysis date Site	11/10/88 A	31/01/89 A	01/02/89 A	08/03/89 A	16/11/89 A	16/11/89 B	17/11/89 A	17/11/89 B
Untrans. D^A	0.0957	0.1303	0.0872	0.1292	0.0881	0.1457	0.1155	0.1162
Log trans. D^B	0.1126	0.0787	0.1644	0.2002	0.1259	0.1081	0.1205	0.2228
Minimum θ (%)	28.3	3.5	4.1	2.2	1.2	1.0	6.5	1.0
Maximum θ (%)	45.5	18.6	29.4	28.3	11.4	23.9	33.2	28.7
C.V.[C] (%)	6.6	32.3	34.6	37.0	30.4	49.9	16.0	53.2

[A] Kolomogorov D statistic for untransformed data.
[B] Kolomogorov D statistic for log transformed data.
[C] Untransformed data.

Table 3.2. Number of sample pairs and corresponding weighting for a nested square grid sampling strategy for geostatistical analysis.

Lag (m)		Number of sample pairs	Weighting, W^A
Nested grid	Main grid		
0.15	2.1	799	0.03222
0.30	4.2	1102	0.04437
0.45	6.3	1350	0.05437
0.60	8.4	2397	0.09643
0.75	10.5	1880	0.07571
0.90	12.6	2372	0.09540
1.05	14.7	2101	0.08460
1.20	16.8	2189	0.08825
1.35	18.9	2600	0.10508
1.50	21	1780	0.07198
1.65	23.1	1854	0.07516
1.80	25.2	1370	0.05563
1.95	27.3	1300	0.05302
2.10	29.4	838	0.03429
2.25	31.5	381	0.01556
2.40	33.6	280	0.01143
2.55	35.7	91	0.00373
2.70	37.8	59	0.00238
2.85	39.9	8	0.00032
3.00	42.0	2	0.00008

[A] Note $\Sigma W = 1.0$.

However, with the exception of the 31/01/89 and 16/11/89 site B data sets, log transformation did not improve (decrease) the D statistic. It was concluded that log transformation prior to geostatistical analysis would be unproductive. Studies of a range of soil types have found that soil water content is normally distributed (Nielson *et al.* 1973; Davidoff and Selim 1988; Bramley and White 1991a).

The coefficient of variation (C.V.) of θ in the Himatangi sand is informative (table 3.1). In a number of studies the C.V. of water content has been found to lie within the range 2.2 - 30 % (Greminger *et al.* 1985; Gajem *et al.* 1981; Davidoff and Selim 1988; Wilding and Drees 1983). The C.V. of θ in the Himatangi sand was found to be relatively low only in the October sampling and following wetting agent application (17/11/89 site A, discussed later). Summer (November to March) values of C.V.(θ) exceeded 30 % and were associated with wide-ranging θ values at each sampling. These findings support previous observations of high spatial variability in the soil moisture content of repellent soils (e.g. Bond 1964; Hendrickx *et al.* 1988a).

Geostatistics

No evidence of anisotropy was detected from the variograms of N-S and E-W $\hat{\gamma}(\mathbf{h})$ values. Unfortunately there is no statistical test for anisotropy (Laslett *et al.* 1987) and the geometric model for anisotropy testing (Trangmar *et al.* 1985) has limited objectivity (Bramley and White 1991b). Assumption of isotropy greatly increased the number of sample pairs for $\hat{\gamma}(\mathbf{h})$ calculation. In the N-S, E-W analysis the number of sample pairs ranged from 15 to 225. When isotropy was assumed and the lags were grouped into lag classes (table 3.2), 24 lags had over 1000 sample pairs. When the variograms were plotted the $\hat{\gamma}(\mathbf{h})$ values for h = 2.85, 3.0, 39.9 and 42.0 m were omitted due to their low number of sample pairs.

A summary of results for the geostatistical analyses is given in table 3.3 and the corresponding variograms given in figures 3.5a-h. The sample variance, s^2 of each data set (table 3.3) is plotted on the respective variograms:

Table 3.3. Summary of results for the geostatistical analysis of volumetric water content (0 - 200 mm depth) in repellent Himatangi sand.

Analysis date Site Corresponding figure	11/10/88 A 3.5a	31/1/89 A 3.5b	1/2/89 A 3.5c	8/3/89 A 3.5d	16/11/89 A 3.5e	16/11/89 B 3.5f	17/11/89 A 3.5g	17/11/89 B 3.5h
Mean	39.3	7.3	16.3	13.8	4.5	5.4	19.2	10.2
Sample variance, s^2	6.7	5.5	31.7	26.2	1.8	7.2	9.5	29.3
s^2 (nested grid only)	2.7	2.9	19.6	12.4	0.9	5.6	5.5	30.2
s^2 (main grid only)	10.0	8.2	43.4	26.9	1.5	7.6	13.3	27.9
Best-fit model	Sph[A]	Sph[A]	Sph[A]	Sph[A]	Sph[A]	Lin[B]	Exp[C]	Lin[B]
SS(residual)[D]	0.0258	0.0401	0.4906	0.2145	0.0017	0.0566	0.0859	1.756
Range, a (m)	14.6	9.1	7.8	10.2	8.4	-	14.8	-
Nugget variance, C_o	1.8	1.9	13.5	9.0	0.8	5.2	3.5	28.9
Sill variance, $C_o + C$	10.8	8.2	43.6	27.8	1.5	-	14.0	-
Slope, k	-	-	-	-	-	0.156	-	0.016

[A] Denotes spherical variogram model.
[B] Denotes linear variogram model.
[C] Denotes exponential variogram model.
[D] Residual sum of squares for the best-fit model.

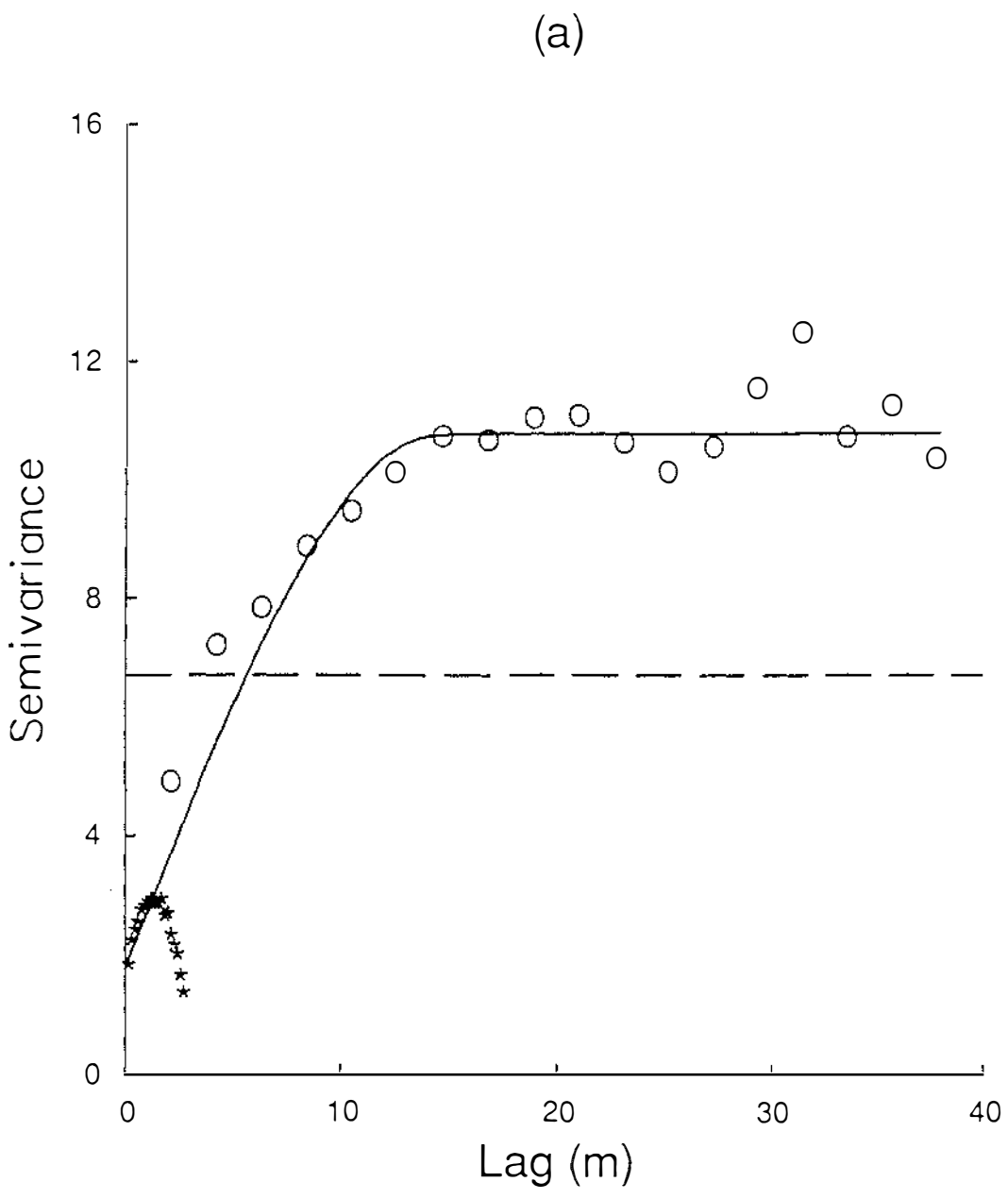


Figure 3.5(a). Smoothed isotropic variogram of volumetric soil water content (0 - 200 mm depth) in the Himatangi sand on 11/10/88 at site A. The semivariance estimates generated from the nested grid (*), the semivariance values estimated from the main grid (○) and the sample variance (broken line) are indicated.

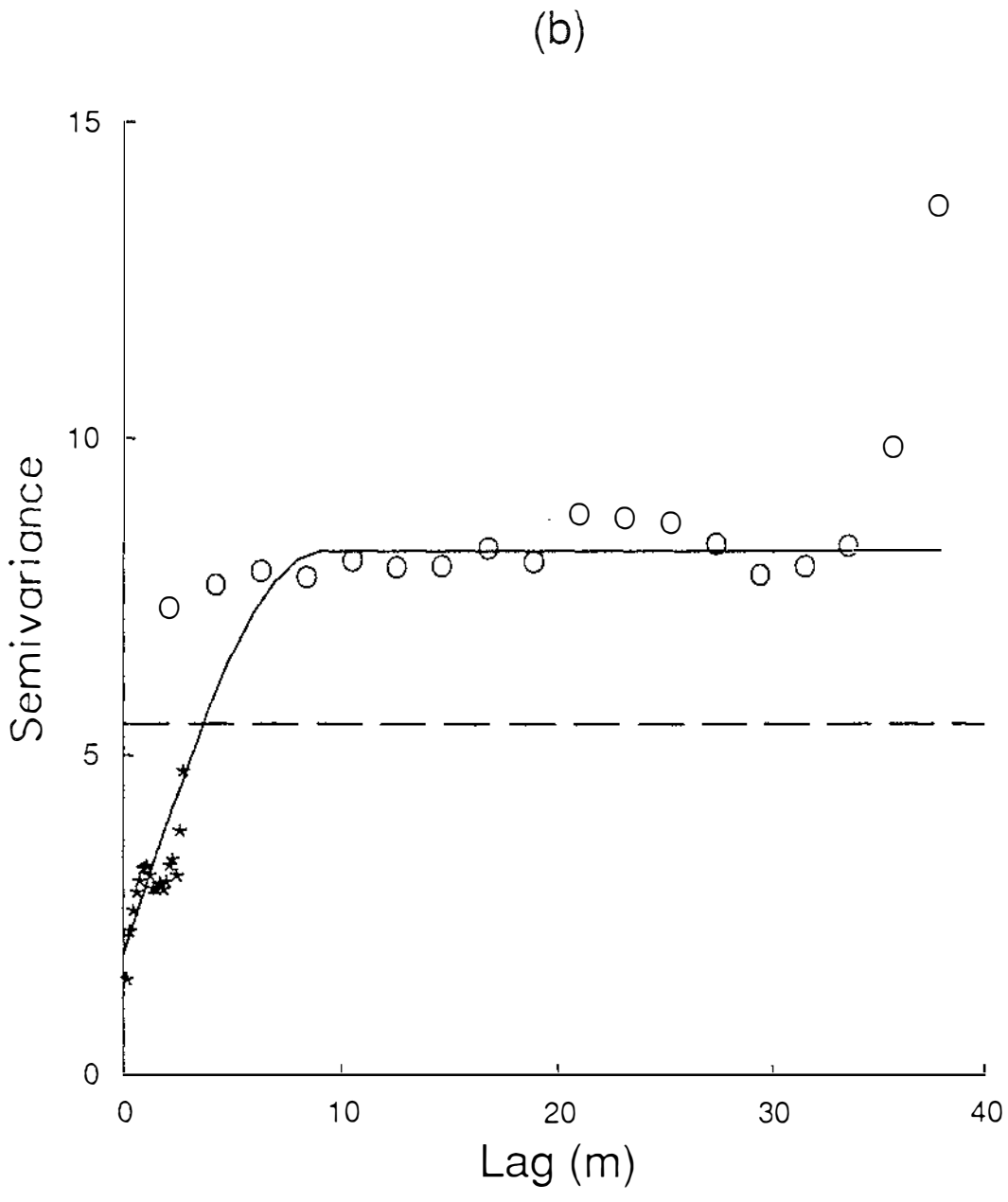


Figure 3.5(b) Smoothed isotropic variogram of volumetric soil water content (0 - 200 mm depth) in the Himatangi sand on 31/01/89 at site A before irrigation. The semivariance estimates generated from the nested grid (*), the semivariance values estimated from the main grid (○) and the sample variance (broken line) are indicated.

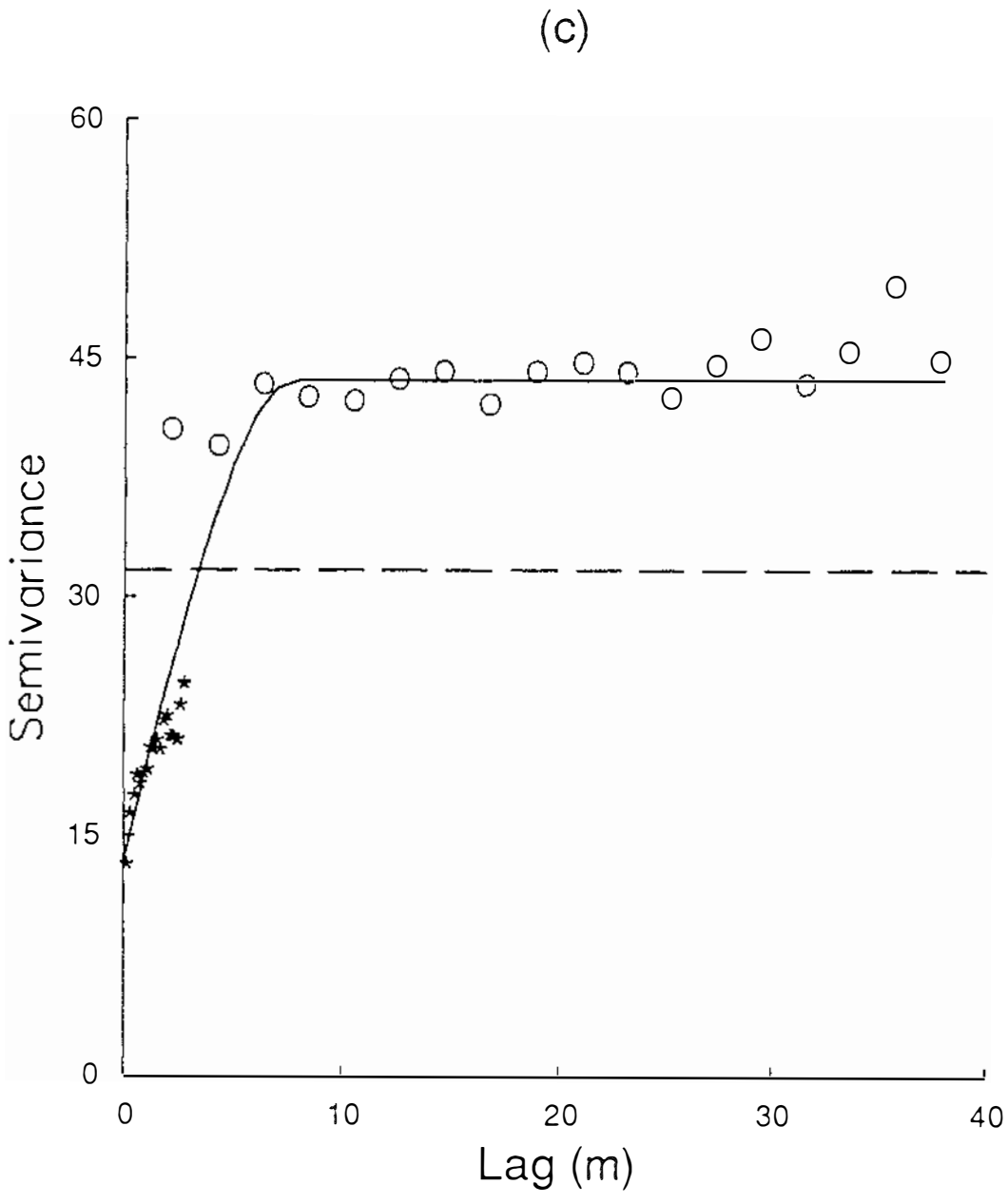


Figure 3.5(c). Smoothed isotropic variogram of volumetric soil water content (0 - 200 mm depth) in the Himatangi sand on 01/02/89 at site A after irrigation. The semivariance estimates generated from the nested grid (*), the semivariance values estimated from the main grid (○) and the sample variance (broken line) are indicated.

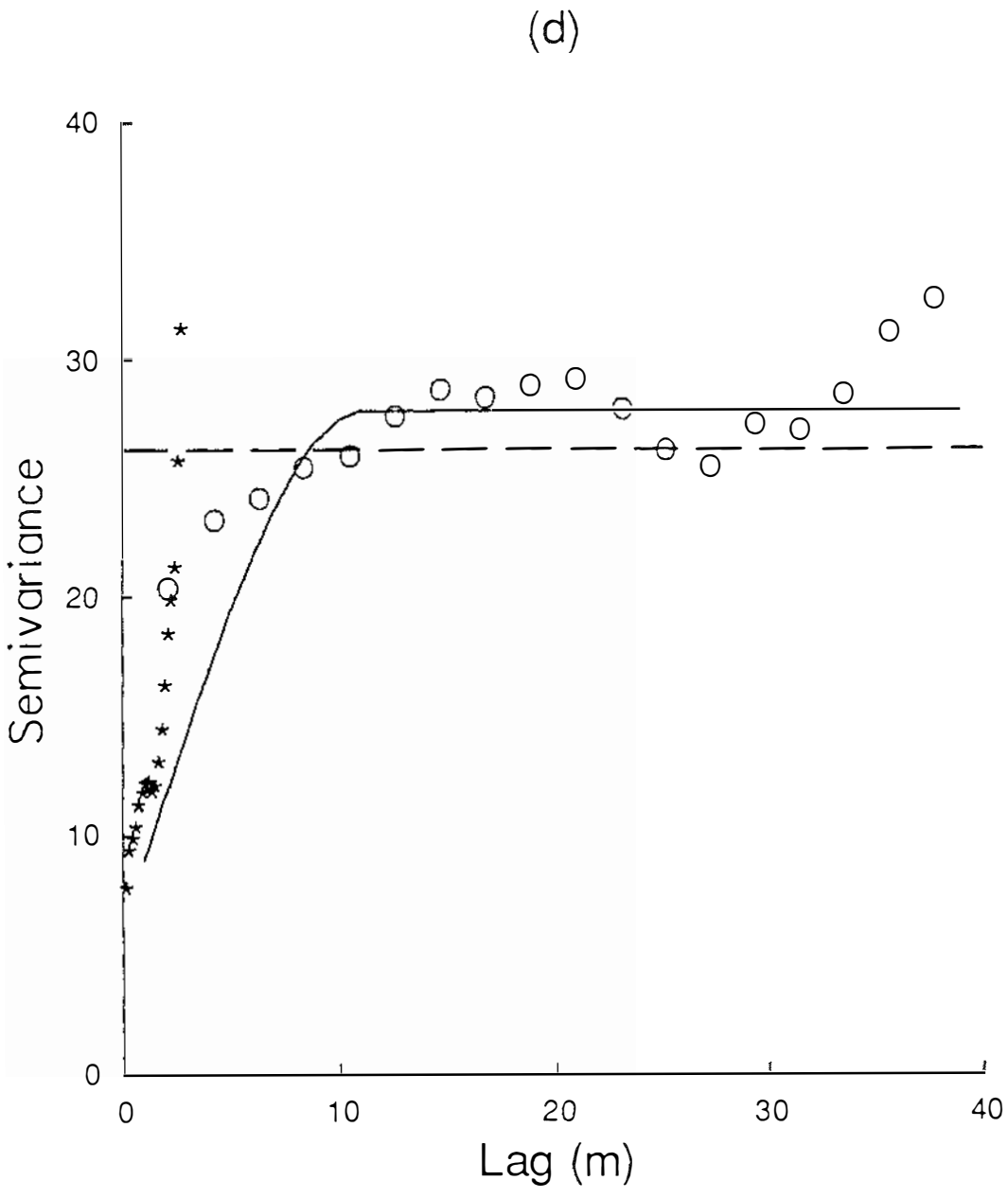


Figure 3.5(d). Smoothed isotropic variogram of volumetric soil water content (0 - 200 mm depth) in the Himatangi sand on 08/03/89 at site A. The semivariance estimates generated from the nested grid (*), the semivariance values estimated from the main grid (○) and the sample variance (broken line) are indicated.

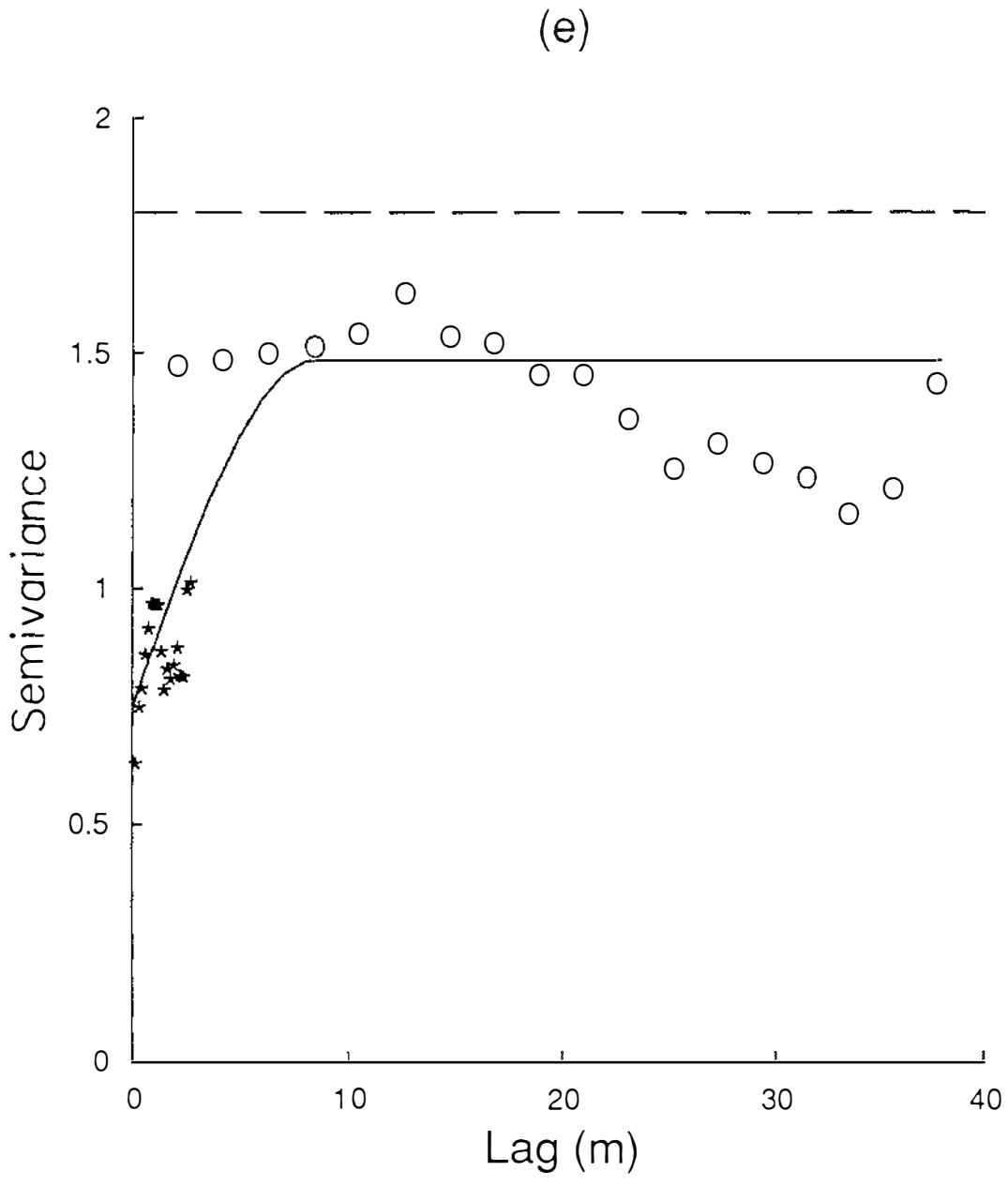


Figure 3.5(e). Smoothed isotropic variogram of volumetric soil water content (0 - 200 mm depth) in the Himatangi sand on 16/11/89 at site A before irrigation. The semivariance estimates generated from the nested grid (*), the semivariance values estimated from the main grid (○) and the sample variance (broken line) are indicated.

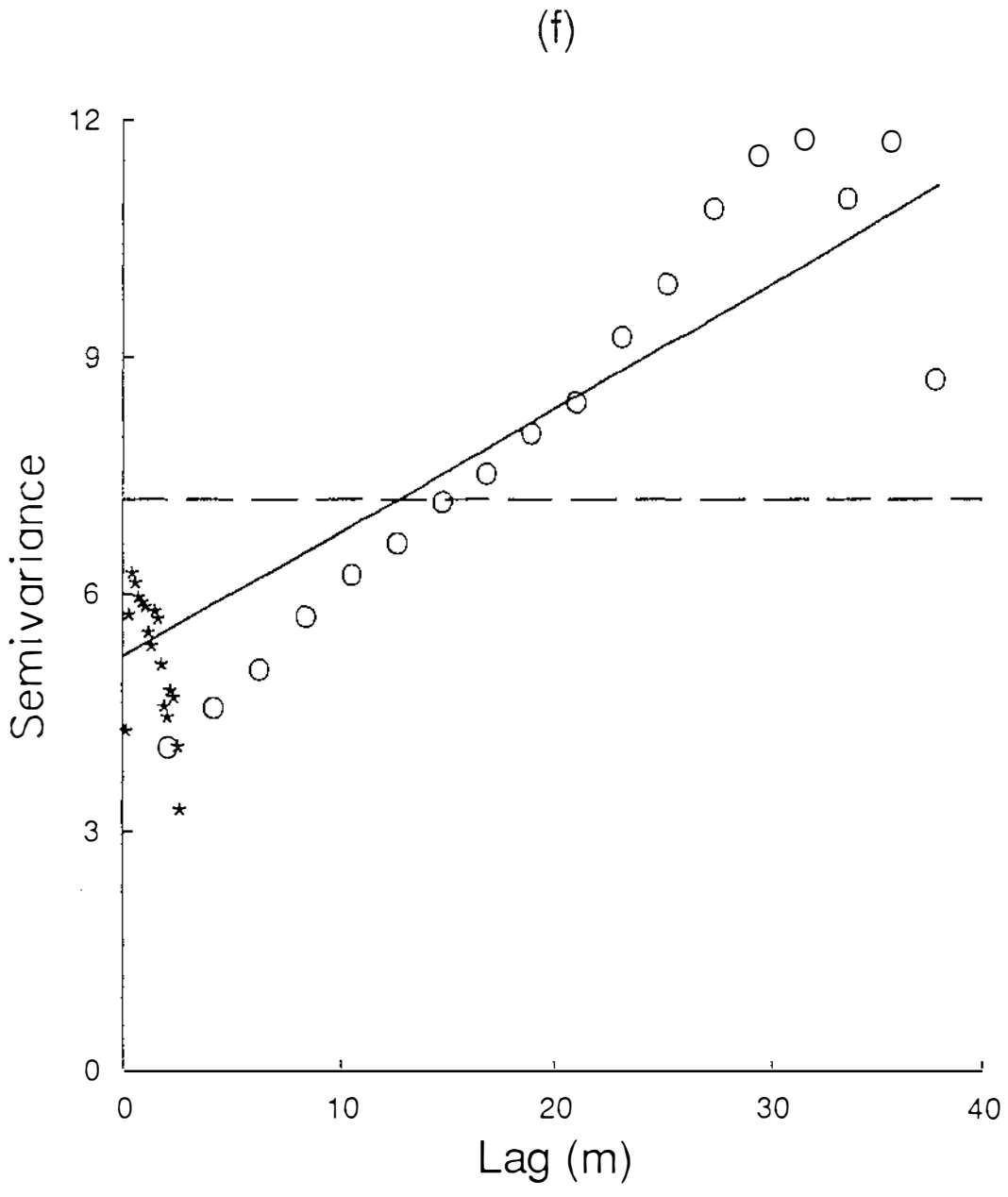


Figure 3.5(f). Smoothed isotropic variogram of volumetric soil water content (0 - 200 mm depth) in the Himatangi sand on 16/11/89 at site B before irrigation. The semivariance estimates generated from the nested grid (*), the semivariance values estimated from the main grid (○) and the sample variance (broken line) are indicated.

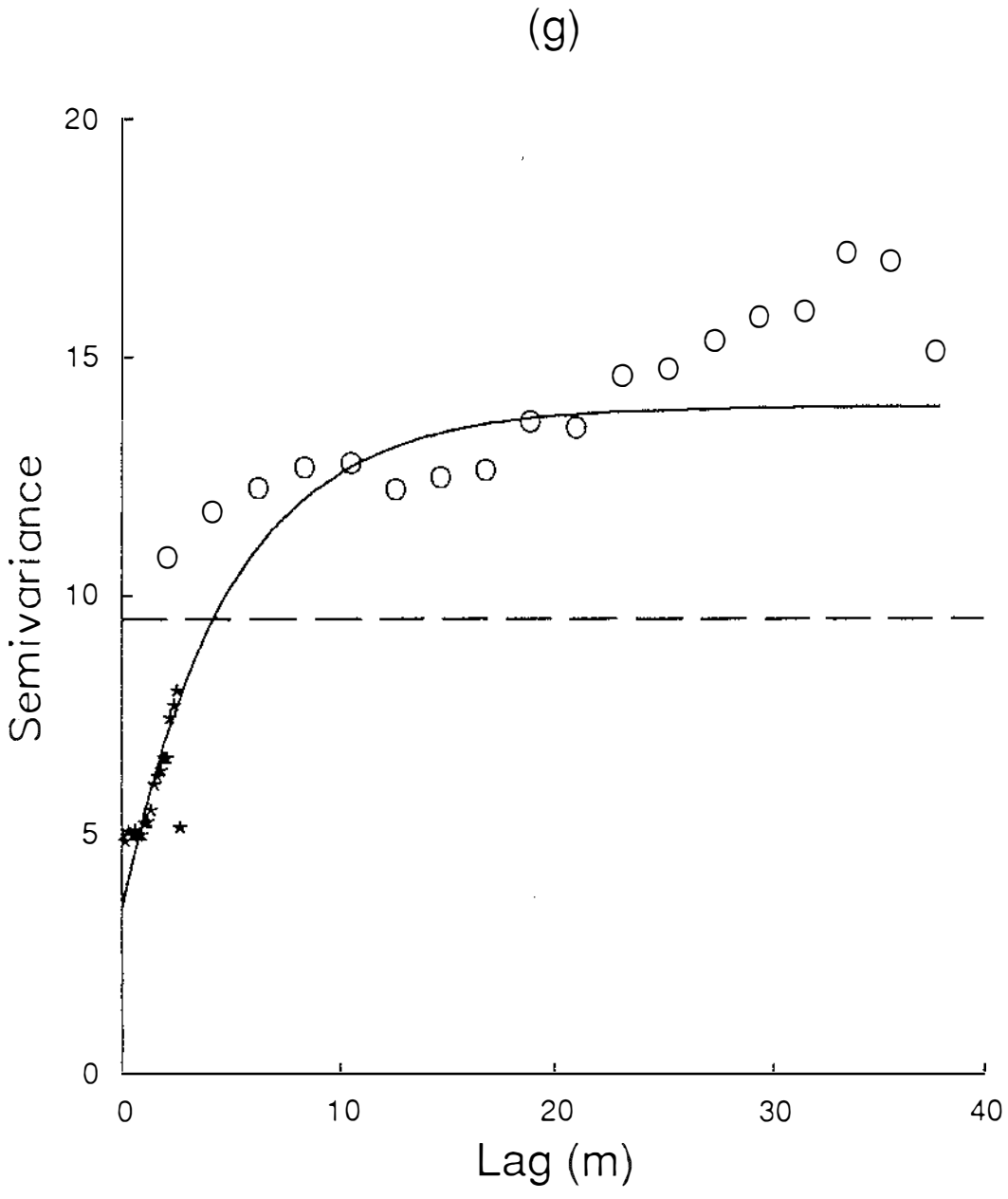


Figure 3.5(g). Smoothed isotropic variogram of volumetric soil water content (0 - 200 mm depth) in the Himatangi sand on 17/11/89 at site A after wetting agent application and irrigation. The semivariance estimates generated from the nested grid (*), the semivariance values estimated from the main grid (○) and the sample variance (broken line) are indicated.

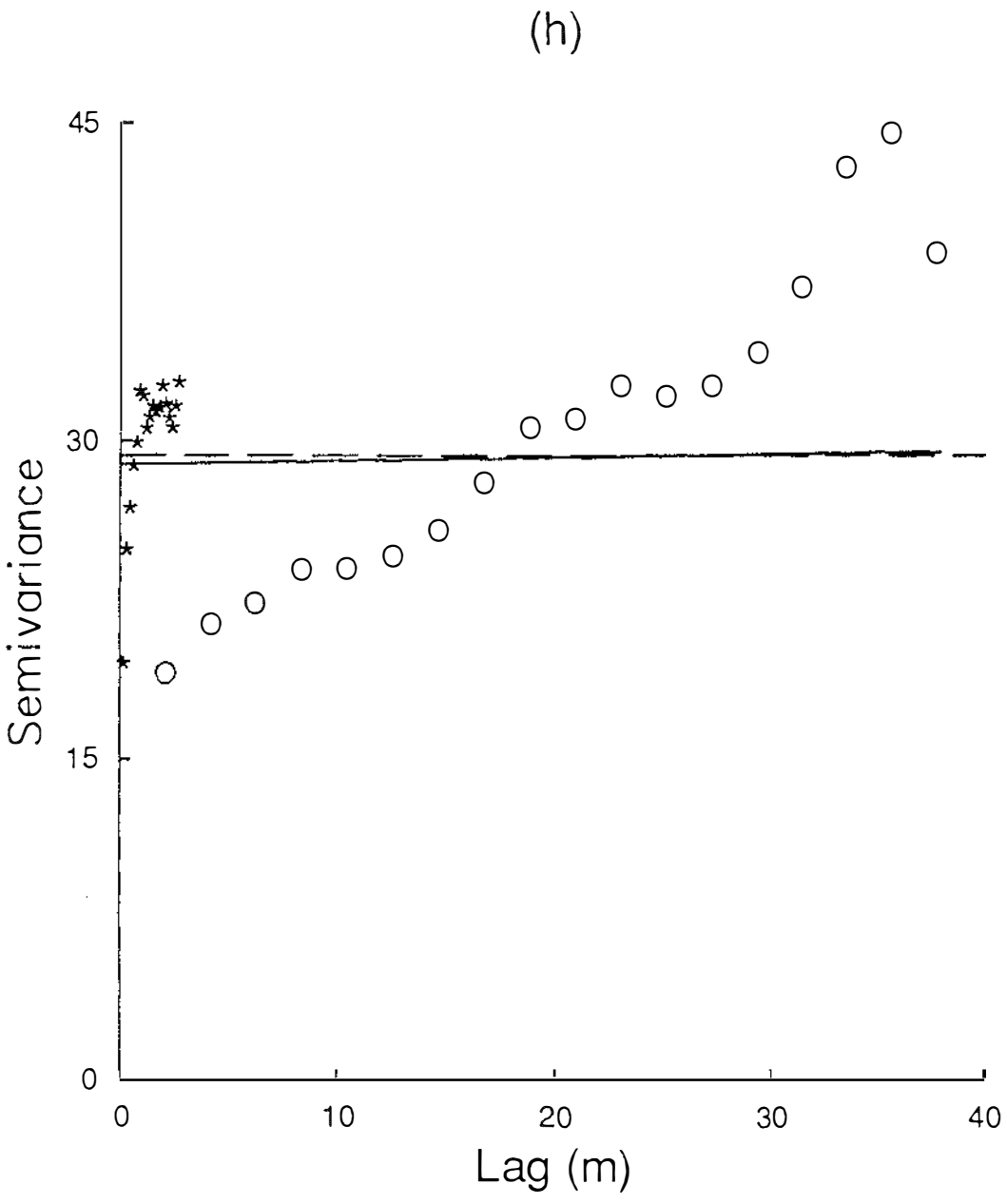


Figure 3.5(h). Smoothed isotropic variogram of volumetric soil water content (0 - 200 mm depth) in the Himatangi sand on 17/11/89 at site B after irrigation. The semivariance estimates generated from the nested grid (*), the semivariance values estimated from the main grid (○) and the sample variance (broken line) are indicated.

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}[\theta(x_i) - \bar{\theta}]^2 \qquad (11)$$

where $\bar{\theta}$ is the sample mean value of θ.

The variograms for all but the 16/11/89, site B and 17/11/89 sampling dates were best-fitted by spherical models of the general form:

$$\hat{\gamma}(\boldsymbol{h}) = C_o + C[1.5\boldsymbol{h}/a] - [(h/a)^3/2];\ 0<\boldsymbol{h}<a$$
$$\hat{\gamma}(\boldsymbol{h}) = C_o + C;\ \boldsymbol{h}>a \qquad (12)$$

where:

C_o is the variance at lag, $\mathbf{h} = 0$, or the 'nugget variance'. The nugget variance includes the variation unresolved by the sampling interval, variation due to measurement error and any purely random variation (Webster 1985);

$C_o + C$ is the maximum or 'sill variance';

a is the lag at which the sill is reached, the limit of spatial dependence or 'range'.

The 16/11/89 and 17/11/89 site B variograms were best-fitted by linear variograms of the general form:

$$\hat{\gamma}(\boldsymbol{h}) = C_o + k\boldsymbol{h};\ h>0 \qquad (13)$$

where k is the slope of the variogram. The linear model has no sill, and therefore no range. When $k = 0$ the variogram is said to be 'pure nugget', indicating no spatial dependence in the data at the scale sampled. For the 17/11/89 site B data $k \approx 0$.

The 17/11/89 site A variogram was best-fitted by an exponential variogram of the general form:

$$\hat{\gamma}(\boldsymbol{h}) = C_o + C[1-\exp(-\boldsymbol{h}/r];\ \boldsymbol{h}>0 \qquad (14)$$

Here, r is a distance parameter which controls the spatial extent of the function (Webster 1985). In the exponential model, $\hat{\gamma}(\mathbf{h})$ approaches the sill asymptotically and there is no

definable range. However, since the semivariance must cease to increase beyond a certain point, the range is taken to be equal to 3r, where $\hat{\gamma}(\mathbf{h})$ is approximately equal to C_o + 0.95C (Webster 1985). Oliver and Webster (1987) pointed out that this approach may overestimate the range compared to the spherical model which curves more tightly to reach the sill variance.

1. The Nested Grid Design

As previously identified, the sampling strategy produced many sample pairs for each determination of $\hat{\gamma}(\mathbf{h})$ (table 3.2), and would therefore be expected to produce reliable $\hat{\gamma}(\mathbf{h})$ estimates. However, Bramley and White (1991b) pointed out that designs in which all nested sites are located in one area may introduce bias in the estimates of $\hat{\gamma}(\mathbf{h})$ and s^2.

Evidence of bias in the $\hat{\gamma}(\mathbf{h})$ estimates produced by the nested design is apparent in the discontinuities between the values of $\hat{\gamma}(\mathbf{h})$ generated from the nested and main grids of both site A and B (fig. 3.5a-h). Bramley and White (1991b) suggested that nesting should reduce s^2 of a property with spatially dependent variability. To test this hypothesis the s^2 values of the nested and main grids were calculated for each sampling date (table 3.3). The s^2 value of the nested grids was less than that for the respective main grids for all variograms except that for 17/11/89 site B, for which the pure nugget model suggests that variance at the shortest lags was equivalent to that of greater lags. It would appear that the nested grid sampling strategy used produced bias in the estimates of $\hat{\gamma}(\mathbf{h})$ and s^2. Such bias could be reduced by sampling a number of nested grids within the main grid or spreading the short lags throughout the main grid (Bramley and White 1991b).

The value of the sample variance, s^2 is expected to be less than that of the sill variance (Bramley and White 1991b). All of the Himatangi sand water content variograms with a defined sill variance except that for 16/11/89 site A (fig. 3.5e) conformed to the above expectation. Bramley and White (1991a) generated variograms for soil nitrification, nitrate level and water content in which the values of $\hat{\gamma}(\mathbf{h})$ appeared to be low relative to s^2. They suggested that this was due to unequal reference to sampling sites in the estimation of the variogram and log transformation. This explaination is unlikely to apply to variogram (1e)

because, although there would be some inequality in accessing sample sites in the calculation of $\hat{\gamma}$ at certain lags, the data was not markedly skewed and hence bias in the value of $\hat{\gamma}$ at these lags, relative to the value of s^2, should not be expected.

2. Seasonal Pattern of Water Content Variability

The immediately apparent feature of the soil water content variograms (fig. 3.5a-h) is the variation in $\hat{\gamma}(\mathbf{h})$ and s^2 with the time of sampling. The variability of water content in the Himatangi sand therefore had both a temporal and a spatial component. Bramley and White (1991b) found that a number of biological soil properties also had temporal variability, in contrast with soil physical properties. They pointed out that variograms of soil physical properties such as texture can also be transferred between sampling areas of similar soil type and topography. It does not appear that the Himatangi sand water content variogram is readily transferable. The variograms for the adjacent sites A and B sampled on 16/11/89 and 17/11/89 were quite different (fig. 3.5e,f,g,h). The site B variograms were both linear, with the trend of the data suggesting drift in the mean which did not appear to be present in the variograms for site A. There was no obvious reason for drift of the mean water content at site B but not site A, such as topographical differences between the sites.

Disregarding the post-wetting agent treatment (fig. 3.5g), the variograms of water content in the Himatangi sand (fig. 3.5a-f) did not display a consistent seasonal trend in variance. The nugget and sill variance of the 11/10/88 and 31/01/89 sampling dates were markedly similar, for example. However, the nugget variances (table 3.3) of the summer (November to March) variograms were relatively large compared to the respective sill variances, indicating that in summer the moisture content varies widely over short distances. By contrast, in the October evaluation the nugget variance was small relative to the sill variance. Furthermore, the summer soil water content coefficients of variation consistently exceeded that of the October evaluation, as noted previously (table 3.1). The frequency distribution analysis conducted was therefore most useful for consideration of the variance in relation to the mean.

The range of spatial dependence in θ was consistently between 8 - 10 m in summer (disregarding the post-wetting agent treatment and the site B variograms). The range increased to 15 m in October, when the mean soil water content approached saturation (Swain and Scotter 1988). Severely repellent sand may only wet up slowly over the winter months after extended periods of rainfall (Jamison 1945). Repellent soil may also wet up by capillarity from a rising water table (Hendrickx *et al.* 1988a). The depth to the water table at the Himatangi sand site was 0.77 m on 11/10/88 and $>$ 1 m on all summer sampling dates. Scotter (1989) used an analysis based upon the water statics and dynamics of a yellow-brown sand similar to the Himatangi sand to indicate that a water table at $<$ 1 m depth would affect the water content of the surface soil.

The range of θ measured at each sampling date may indicate zones of water infiltration and movement through relatively less repellent soil (Hendrickx *et al.* 1988a). The results indicate that in the Himatangi sand the zones are relatively large in winter but contract in summer. Although the ranges of spatial dependence suggest large zones (8 - 15 m), the high nugget variances in summer noted previously indicate that preferential flow pathways in the Himatangi sand may be relatively localised. Excavation and visual examinations of water movement following irrigation may help to elucidate the size, nature and persistence of any such flow pathways.

Bond (1972) found that establishment and growth of barley on repellent Australian sand was patchy and related to the severity of repellency and consequent soil moisture content. Wallis *et al.* (1990a) measured very poor plant emergence in seed trays of dry, repellent Himatangi sand. In the field, newly sown pasture growth was poorer in untreated Himatangi sand than in plots treated with wetting agent to increase infiltration (Wallis *et al.* 1990b).

3. Irrigation and Water Content Variability

An application of 45 mm irrigation to site A increased the nugget and sill variance dramatically (fig. 3.5b,c) and increased the coefficient of variation slightly from 32.3 - 34.6 % (table 3.1). Irrigation of site B (fig. 3.5f,h) also increased the nugget variance

dramatically and increased C.V.(θ) slightly from 49.9 to 53.2 %. The application uniformity of the travelling boom irrigator was high and would not account for the increased variability in soil water content observed at each site. At site A the range of spatial dependence of the soil water content decreased slightly from 9 to 8 m. The average increase in soil water content was equivalent to 18 mm water, which suggested that *c.* 27 mm had either moved below 200 mm depth or had run off the grid area. At site B, irrigation increased soil water by 9.6 mm, leaving *c.* 35 mm of water unaccounted for. The lower mean water content increase at site B compared to site A may have been the result of lower initial mean water content at site B, and consequently more severe repellency (Wallis *et al.* 1990a). Runoff was most likely to be at least partly responsible for the unaccounted water at both sites because the irrigator application rate greatly exceeded the infiltration rate of dry, repellent Himatangi sand (Wallis *et al.* 1990a, 1991).

4. Wetting Agent Application, Irrigation and Water Content Variability

When 100 l ha^{-1} of wetting agent was applied to the Himatangi sand prior to a 45 mm irrigation event, the nugget and sill variance increased by less than that caused by irrigation alone (fig. 3.5e,g). In contrast to the irrigation-only treatment of site A (fig. 3.5b,c) and site B (fig. 3.5f,h) the coefficient of variation actually decreased after irrigation from 30.4 - 16% (table 3.1). The wetting agent produced a more uniform soil water content after irrigation, which was consistent with the small-scale (soil core) findings of Sawada *et al.* (1989). In further contrast to the irrigation-only treatment of site A, the range of θ spatial dependence increased from 8 to 15 m after irrigation when the wetting agent was applied. Prior to the wetting agent treatment the soil had a lower water content than before the irrigation-only treatments of either site A or B. The soil would be expected to be more severely repellent at the lower water content (Wallis *et al.* 1990a); however, the soil water content increased by the equivalent of 29.4 mm when the wetting agent was used, which exceeded the increase due to irrigation-only by 63 % over site A and 206 % over site B. Presumably the wetting agent treatment increased the soil infiltration rates and reduced surface water redistribution from the experimental site.

Conclusions

The nested grid sampling strategy produced a high number of sample pairs for estimates of the semivariance, but bias in the semivariance and sample variance estimates appeared to result from the location of all the nested sites in one area of the main grid.

Volumetric soil water content (θ) in the Himatangi sand was generally best described by a normal frequency distribution. The variograms of θ changed over time and did not appear to be transferable between sites of close proximity, although there was evidence of drift in the mean at site B. Geostatistical techniques appeared to have some limitations for investigating the spatial variability of θ in repellent Himatangi sand.

The variability of θ in summer consistently exceeded that observed in October. In summer θ was spatially dependent within a range of 8 - 10 m, which increased to 15 m in October. Despite the range of spatial dependence indicated by the site A variograms, relatively high nugget variance in summer indicated that soil moisture varied widely over short distances.

Irrigation increased the variation of θ but did not change the range of spatial dependence to an appreciable extent. Application of a wetting agent prior to irrigation halved the coefficient of variation of θ and increased the range of spatial dependence. The wetting agent increased the amount of irrigation water stored in the soil profile to 200 mm depth compared to irrigation-alone.

These results indicate that soil water repellency reduced irrigation water infiltration, increased water content variability and affected the spatial distribution of soil water.

Acknowledgements

The authors wish to thank the farmers, Mr. and Mrs. Greig for their cooperation, Mr. I. Furkert and Mrs. H. Murphy for technical assistance, and Prof. R.E. White for comment on the manuscript.

CHAPTER FOUR: WATER REPELLENCY IN A DEVELOPMENT SEQUENCE OF YELLOW BROWN SANDS

4.0 INTRODUCTION

Soil development sequences have been used extensively to improve the understanding of soil genetic processes since Jennny (1941) further developed the concepts of the Russian, Dokuchaiev, who published in an obscure journal in 1898 that soils are products of extremely complex interactions of local climates, plants and animals, parent rocks, topography, and the ages of landscapes (Jenny 1961). Jenny's most important deduction was that one single 'state factor', for example time, may outrank the combined influence of all the other factors upon soil development.

Chronosequences, in which the age of a series of soils dominates their development, have been used widely to study many soil processes (e.g. Jenny *et al.* 1949; Crocker and Dickson 1957; Vreeken 1975). However, true 'chronosequences' are not found in nature because it is not possible for all state factors other than time to remain independent of the time variable. Therefore we have chosen to use the terminology 'soil development sequence'.

A development sequence of soils developed upon wind-blown sands in the Manawatu district of New Zealand has been used to study organic matter accumulation and dynamics (Syers *et al.* 1970; Goh and Reid 1975; Goh *et al.* 1976; Goh and Williams 1979; Williams and Goh 1982). These studies utilised a range of soils under pasture and native vegetation from a transect of sand dunes.

The soils of the development sequence were classified in the 'yellow-brown sand' group by Taylor (1948). Cowie (1963) recognised distinct dune-building phases in the yellow-brown sands of the Manawatu. He described the dunes of the Waitarere Phase as a coastal belt 400 m to 3 km wide, and cited early European records of dune destabilisation to date the Waitarere phase at $<$ 130 years old.

Cowie (1963) named the next oldest series of dunes and sand plains the Motuiti Phase, which form a belt up to 10 km wide inland of the Waitarere dunes. The native vegetation of the dunes, which comprised manuka (*Leptospermum ericoides*), bracken fern (*Pteridium esculentum*) and tutu (*Coriaria* spp.) has been largely replaced by browntop grass (*Agrostis tenuis*) and subterannean clover (*Trifolium subterraneum*), however the sand plains can support ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) pasture. Radiocarbon dating and the position of buried Maori occupation material indicated that the Motuiti dunes started to advance about 750 years ago. The degree of soil profile development further lead Cowie to conclude that the Motuiti dunes became stabilised about 500 years ago.

The dunes of the Foxton Phase form a 3 to 6 km wide belt inland of the Motuiti dunes (Cowie 1963). The dunes and plains now support similar plant species to those described for the Motuiti Phase. Tephra chronology and the degree of soil development lead Cowie to date the Foxton Phase as 2000 to 4000 years old. Shepherd (1987) used ^{14}C dating to determine that the most inland Foxton dunes became stabilised c. 1600 y B.P. From calculation of dune advancement rates, he estimated that the Foxton phase dunes would have commenced at the coastline c. 6000 years ago.

Cowie (1963) found that the oldest dune phase, Koputaroa, was only found in small areas of northern and southern Manawatu. He explained that the limited extent may be due to a formative relationship with river courses rather than with the sea. However Shepherd (1985) examined the roundness and heavy metal content of Koputaroa dune sand, which indicated that some of the sand, at least, was derived from a marine rather than a fluvatile source. The dunes have a gentle rolling relief and mostly support ryegrass/white clover pasture. Cowie (1963) presented evidence to suggest that the dunes are 10-15 000 years old. Subsequent dating of the interbedded Aokautere ash (Wilson *et al.* 1988; Fleming 1972) would place the Koputaroa Phase at c. 22 500 years old, although now the Koputaroa dune phase is considered to have been developed over the same period as that for Ohakean loess deposition (10 000 - 25 000 years old).

Cowie *et al.* (1967) and Cowie (1968) described the pedology of the yellow-brown sands which comprise the soil development sequence. Profile diagrams (fig. 4.1) show

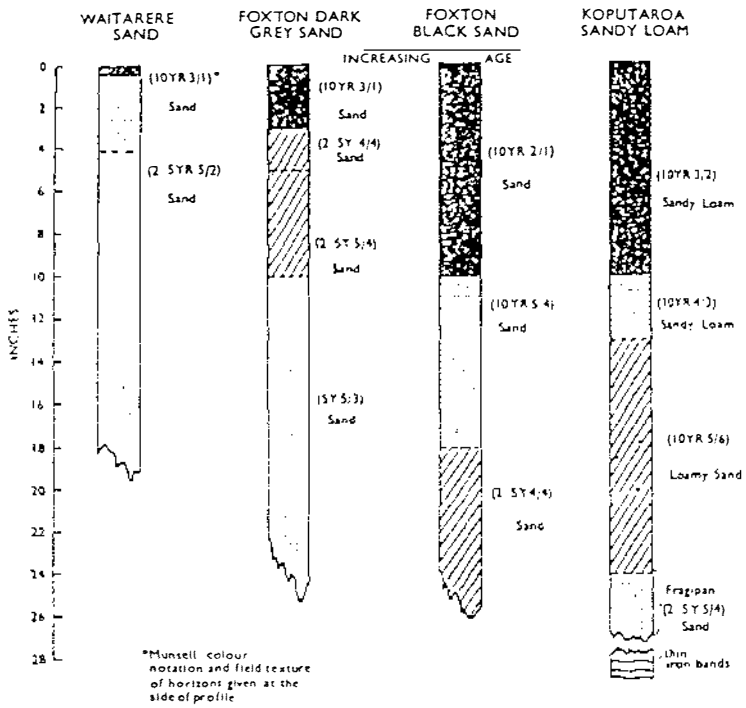


Figure 4.1. Profile diagrams of dune soils showing changes with increasing age. Munsell colours and textures of the horizons are shown on the right of each diagram (Cowie 1968).

increasing soil development with increasing age. Soil structural development ranged from weak aggregation in the Waitarere sand to strongly developed granular structure in the Koputaroa sandy loam.

Cowie *et al.* (1967) and Cowie (1968) described the marked effect of relief upon soil development within a dune phase (fig. 4.2). Cowie (1968) pointed out that the range of relief affects the soil microclimate, including soil temperature and moisture, and the vegetation. A diagram of the basic dune unit is given in figure 4.3.

Cowie *et al.* (1967) and Cowie (1968) gave full profile descriptions for all the soils he recognised in the yellow-brown sand development sequence. The soils investigated in this study are depicted in the photographs (fig. 4.4 - 4.11). Figure 4.12 also illustrates the relationship of the soils with respect to age and relief. Cowie (1968) noted that soils developed under scrub, such as the Foxton black sand, had a very dark brown (10YR 2/2) or black (10YR 2/1, 7.5YR 2/1) topsoil coloration, but those developed under forest, such as the Foxton brown sand, had a greyish brown (10YR 3/2) or reddish brown (5YR 3/2) topsoil. Bracken fern is known to impart very black soil coloration (Birrell 1966).

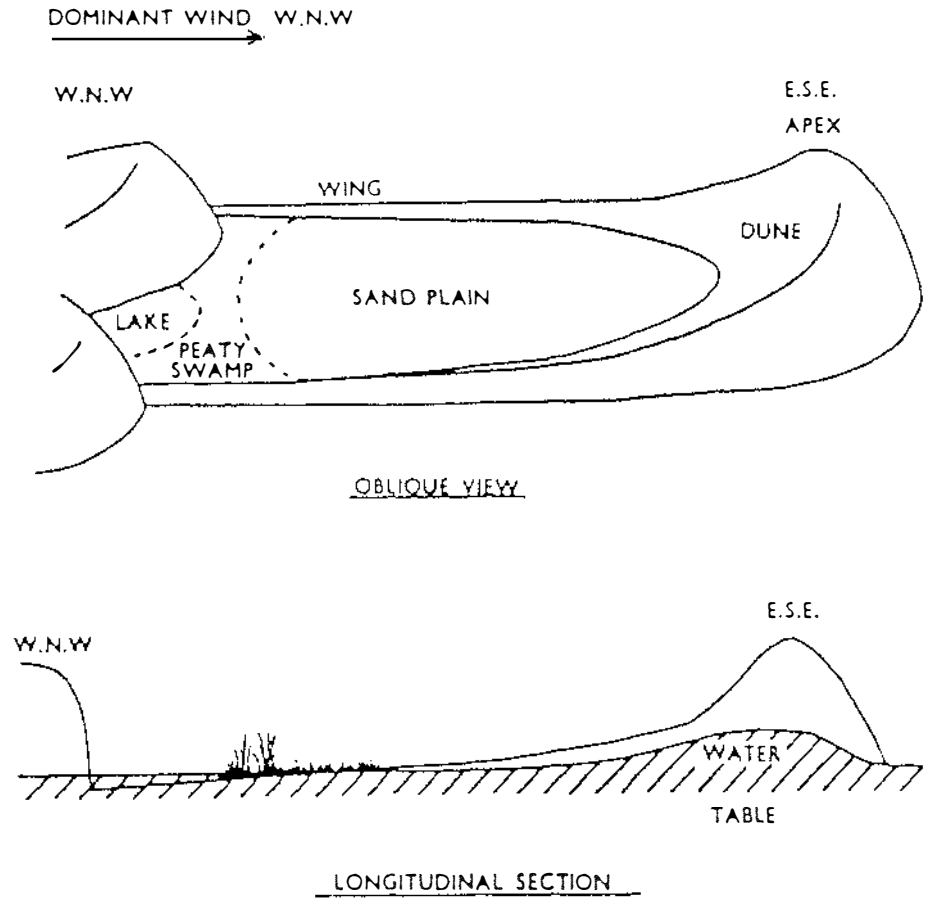


Figure 4.2. Diagram of soil-profile features in relation to the dune unit and to drainage. (NOTE: The symbol for yellowish grey horizon shown in the legend refers to the lowermost part of the column for Awahou sandy loam or loamy sand) (Cowie *et al.* 1967).

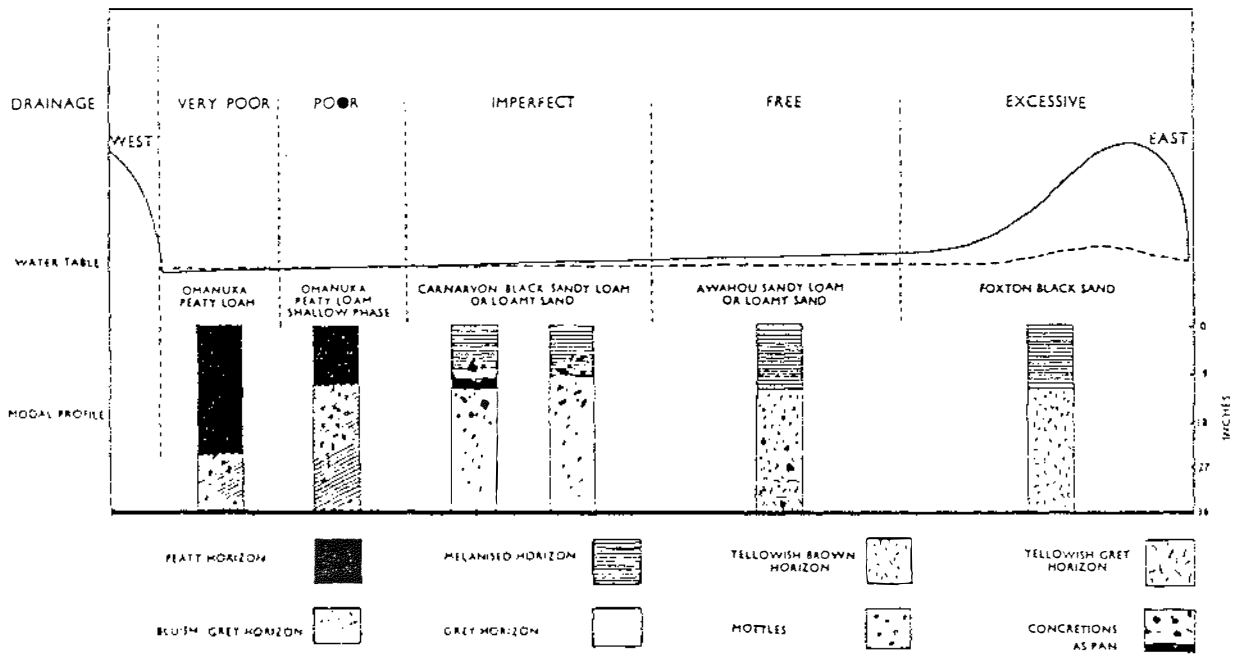


Figure 4.3. Diagram of basic unit of dune ridge, sand plain and peaty swamp (Cowie *et al.* 1967).



Figure 4.4. Waitarere sand (photo M.G. Wallis).

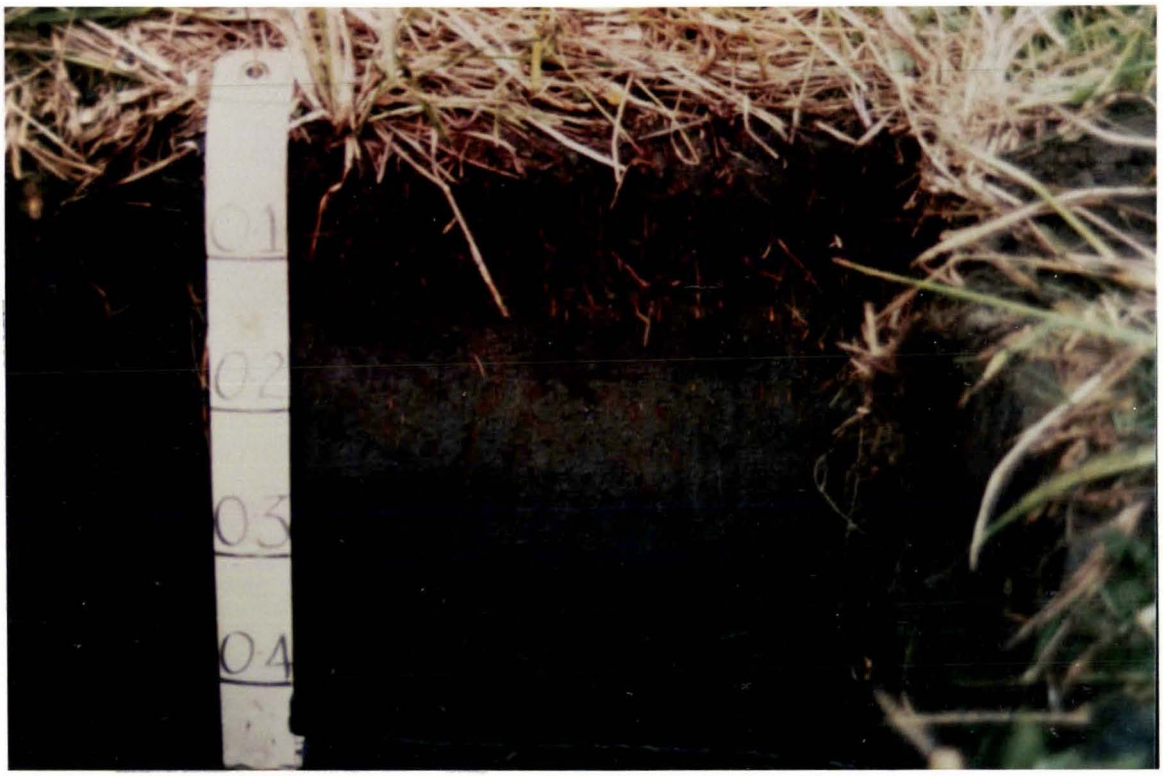


Figure 4.5. Hokio sand, peaty phase (photo M.G. Wallis).



Figure 4.6. Motuiti sand (photo M.G. Wallis).



Figure 4.7. Himatangi sand (photo M.G. Wallis).



Figure 4.8. Pukepuke black sand (photo M.G. Wallis).



Figure 4.9. Foxton black sand (photo M.G. Wallis).



Figure 4.10. Foxton brown sand (photo M.G. Wallis).



Figure 4.11. Koputaroa sandy loam (photo M.G. Wallis).

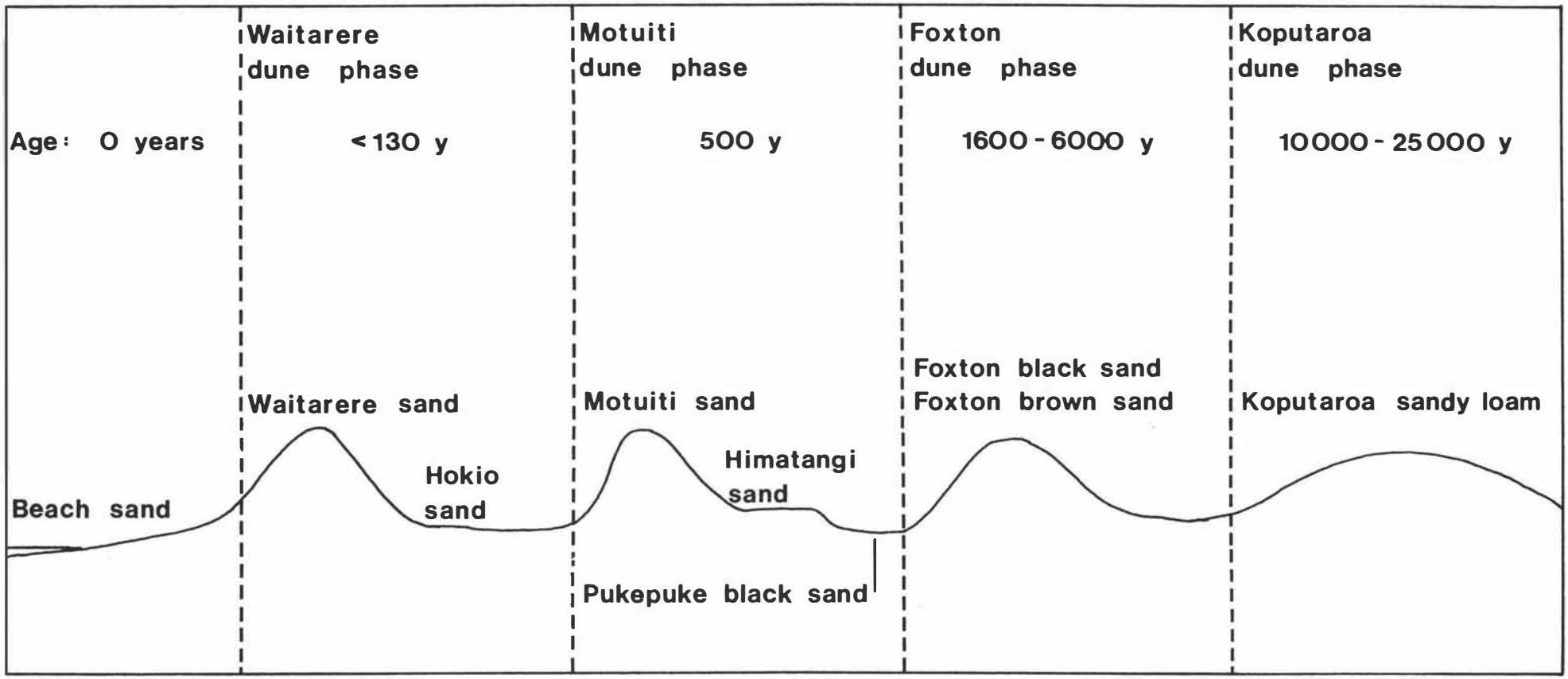


Figure 4.12. Schematic diagram of the age and relative topographic positions of yellow-brown sands used in a study of soil water repellency.

4.1 WATER REPELLENCY IN A DEVELOPMENT SEQUENCE OF YELLOW-BROWN SANDS

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Abstract

A series of sands on the west coast of the lower North Island, New Zealand, were studied to investigate the effects of time, topography and vegetation cover upon the development of soil water repellency. Severe repellency was measured with the molarity of ethanol droplet (MED) index in the Waitarere and Motuiti dune phase sands, of age < 130 y and c. 500 y respectively. In each dune phase the dune sands were more repellent than the lower-lying soils of the sand plains. Low or zero MED values were measured in the 1600 - 6000 y old Foxton dune phase sands and 10 000 - 25 000 y old Koputaroa dune phase sandy loams under either pasture or native bush. There was no consistent relationship between bush or pasture cover and repellency severity in the Foxton and Koputaroa soils, however the species composition of the pasture and bush differed.

The Waitarere sand was the most repellent soil despite a low organic carbon content. The carbon content profiles of most of the soils did not appear to be related to the respective MED profiles of repellency severity. No apparent relationship was found between the humic acid to fulvic acid ratio (HA/FA) and MED or between the FA content and MED in five soils. Neither could MED values be explained by consideration of the soil pH, which affects HA and FA solubility.

A study of soil water content indicated that repellency reduced rainfall infiltration into the Waitarere and Motuiti dune sands and the Himatangi sand, found on elevated sand plains. The most severely repellent sands had the greatest variability in soil water content after

rainfall.

Introduction

Water repellent soils display hydrophobic properties with a consequent reduction in infiltration (Brandt 1969a) which may cause accelerated runoff and erosion (Krammes and Osborn 1969) and reduce plant establishment and growth (Osborn *et al.* 1964; Bond 1972). Wallis *et al.* (1990a,b) have found that the Himatangi sand, a yellow-brown sand (Aquic Udipsamment) found on the west coast of the lower North Island, suffers from severe repellency when dry. The Himatangi sand forms part of a development sequence of yellow-brown sands which has been used to study organic matter accumulation and distribution (e.g. Syers *et al.* 1970; Goh *et al.* 1976). An investigation of repellency in the soils of the development sequence was undertaken to study the development of repellency with time. Sites were selected (Table 1) so that the influences of organic matter, topography and vegetation upon repellency development could be investigated.

Chronosequences, in which the age of a series of soils dominates their development, have been used to study many soil processes (e.g. Jenny *et al.* 1949; Crocker and Dickson 1957; Vreeken 1975). However true 'chronosequences' are not found in nature because it is not possible for all other state factors (Jenny 1961) to remain independent of the time variable. For example in the yellow-brown sand development sequence rainfall ranged from c. 850 mm at the coast to c. 950 mm inland, and vegetation ranged from coastal grasses and scrub to inland forest (Cowie *et al.* 1967). Therefore the term 'development sequence' has been applied to the soils studied.

The soils were classified in the 'yellow-brown sand' group by Taylor (1948) and comprise 2% of the North Island land area (NZ Soil Bureau 1954). Claridge (1961) found that the sand parent material of the soils contained predominantly quartz and feldspar minerals, with small amounts of mica. Most sand grains had a diameter of 0.15 to 0.3 mm and the proportion of silt and clay increased from < 1% in the youngest soil to 10 % silt and 20 % clay in the oldest. He postulated that most of the silt and clay in the older soils was not derived from weathering *in situ* but from wind-blown deposits and volcanic ash.

Cowie (1963) recognised four distinct dune-building phases in the yellow-brown sands. Sharp differences in soil development between each phase indicated that dune formation was discontinuous. He considered that periods of vegetation destruction in response to either climatic change, volcanic eruptions or man's influence have lead to increased sand deposition at the beaches and/or dune destabilisation. Pollen analyses (McIntyre 1963), radiocarbon dating and tephra chronology were used to support this hypothesis (Cowie 1964).

Cowie (1963) reported that the Waitarere Phase is found along a coastal belt 400 m to 3 km wide which was destabilised by overgrazing and burning in the 1860s and is therefore < 130 years old. The dunes and sand plains of the Motuiti Phase form a belt up to 10 km wide inland of the Waitarere dunes. Radiocarbon dating and buried Maori occupation material indicated that the Motuiti dunes started to advance about 750 years ago. From the degree of soil profile development Cowie (1963) concluded that the Motuiti dunes became stabilised about 500 years ago. The dunes of the Foxton Phase form a belt 3 -6 km wide inland of the Motuiti dunes and were dated by Cowie (1963) at 2000 to 4000 years old. Shepherd (1987) found that the most inland Foxton dunes had become stabilised c. 1600 years ago, and would have been initiated at the coast c. 6000 years ago. Cowie (1963) only found the oldest dune phase, Koputaroa, in small areas of northern and southern Manawatu. He explained that their limited extent may be due to a formative relationship with river courses rather than with the sea. He further suggested that the dunes are 10-15 000 years old, however subsequent dating of the interbedded Aokautere Ash (Wilson *et al.* 1988) would date the Koputaroa Phase at c. 22 500 years old. Koputaroa dunes are now considered to be coeval with Ohakean loess (10 - 25 000 y) and have been shown to be of marine origin (Shepherd 1985).

Cowie *et al.* (1967) and Cowie (1968) described the pedology of the yellow-brown sands. The soils showed increasing soil development with increasing age. Cowie (1968) described the marked effect of topography upon soil development within a dune phase and pointed out that topography affects the soil microclimate, including soil temperature and moisture, and the vegetation. Cowie (1968) noted that the topsoil of the Foxton black sand, developed under scrub, was very dark brown or black but the Foxton brown sand, developed under forest, had a greyish or reddish brown topsoil. Bracken fern (*Pteridium*

acquilinum var. *esculentum*) is known to impart very black soil coloration (Birrell 1966).

Repellency is widely acknowledged as the result of an organic coating around soil particles (Bond 1969a). High magnification of repellent sand grains has shown the presence of an organic coating which was not present on sand grains from nonrepellent soil (Wilkinson and Miller 1978; Rankin and Ross 1982). Wallis *et al.* (1990a) reported a relationship between repellency severity and carbon content in the Himatangi sand.

The specific nature of the organic coating surrounding repellent soil particles has been the subject of much research and contention. A number of researchers have proposed that the humic acid (HA) fraction is responsible (Roberts and Carbon 1972; Adhikari and Chakrabarti 1976; Nakaya *et al.* 1977b; Savage *et al.* 1969a). In contrast Miller and Wilkinson (1977) implicated fulvic acid (FA) in repellency development.

The balance between HA and FA in the soil and the soil pH may influence repellency development. Chen and Schnitzer (1978) demonstrated that both HA and FA reduced the surface tension of water significantly, which would increase the rate of water infiltration into repellent soil by decreasing the solid-liquid contact angle. They found that FA was soluble in water at any soil pH value, whereas HA was water soluble only at pH $>$ 6.5. The surface tension of HA and FA solutions also decreased with increased pH. Liming soil to increase pH would therefore increase the ability of resident FA (and HA at pH $>$ 6.5) to increase infiltration into repellent soil. Jackson and Gillingham (1985) reported that lime addition in several New Zealand field trials resulted in rapidly increased soil moisture. The moisture response was most evident in late summer/early autumn, particularly after dry periods. They found that liming had reduced soil repellency as measured by capillary rise and water drop penetration time.

Chen and Schnitzer (1978) noted that if there is a deficiency of FA in the soil solution, repellency would be more severe. Singer and Ugolini (1976) found that the repellency of forest soil and litter was significantly correlated with the HA/FA ratio. FA is known to leach with soil development because of its solubility across the pH range (Schnitzer and Desjardins 1969). As soils develop the HA/FA ratio would tend to increase, with a consequent increase in repellency. Goh and Reid (1975) and Goh *et al.* (1976) used the

yellow-brown sand development sequence to provide evidence for the change in topsoil HA/FA ratio over time. They found that HA was concentrated principally in the surface horizons, especially in the younger soil profiles, and rarely extended below 500 mm. FA extended to 1 m depth, and the amount in the lower horizons increased with increasing soil age.

The purpose of this study was to:

1. Measure the severity of repellency in a range of soils of contrasting age, topographic position and vegetation cover;
2. Identify the relationship between repellency and carbon content in the soils;
3. Determine the relationship between repellency and the topsoil HA/FA ratio, the FA content and the pH of the soils;
4. Evaluate the effect of repellency upon the water content of the soils under natural rainfall.

Methods

The soils and site positions used in this study (table 4.1) were selected in positions as close as possible to the sites used in the study of soil organic matter by Goh *et al.* (1976) (Cowie pers. comm. 1991).

The sites were sampled in late November 1990. Four pits were excavated at each site and bagged soil samples c. 300 g were removed from 0 - 50, 50 - 100, 100 - 150 and 150 - 200 mm depth. Corers 50 mm x 50 mm were used for bulk density measurement from 50 and 150 mm depth, from two pits at each site. Soil samples were air-dried and repellency measured with the Molarity of Ethanol Droplet (MED) test, first proposed by Watson and Letey (1970) and developed by King (1981). The MED test measures the molarity of an aqueous ethanol droplet required for soil infiltration within 10 seconds. Ethanol lowers the liquid surface tension and solid-liquid contact angle, increasing the rate of infiltration into water repellent soil. King (1981) provided the following guidelines for interpretation of MED values: MED = 0, nonrepellent; MED < 1, low repellency; MED 1.0 - 2.2,

Table 4.1. Site descriptions for a development sequence of yellow-brown sands.

Dune Phase	Soil Type	Topographic Position	Current Dominant Plants	Site (NZMS260;S24,25)
--	Beach sand	Mean high water	(Bare of vegetation)	961714
Waitarere	Waitarere sand	Dune	blue lupin[A], bracken[B]	963714
	Hokio sand, peaty phase	Low-lying sand plain	raupo[C], red rush[D]	963713
Motuiti	Motuiti sand	Dune	bracken[B], browntop[E], subterranean clover[F]	974722
	Himatangi sand	High sand plain	browntop[E], sub. clover[F]	974723
	Pukepuke black sand	Low-lying sand plain	browntop[E], sub. clover[F]	975722
Foxton	Foxton black sand[1]	Dune	browntop[E], sub. clover[F]	009689
	Foxton brown sand[2]	Dune	tawa[G]	032686
Koputaroa	Koputaroa sandy loam	Dune	ryegrass[H], white clover[I]	039669
	Koputaroa sandy loam	Dune	tawa[G]	041668

[1]formed under scrub vegetation
[2]formed under forest vegetation
[A]*Lupinus augustifolius*
[B]*Pteridium aquilinum var. esculentum*
[C]*Typha muelleri*
[D]*Leptocarpus simplex*
[E]*Agrostis tenuis*
[F]*Trifolium subterraneum*
[G]*Beilschmiedia tawa*
[H]*Lolium perenne*
[I]*Trifolium repens*

moderate repellency; MED > 2.2, severe repellency. Subsamples of approximately 10 g were placed in petri dishes and lightly pressed flat. MED was tested using an eye-dropper, stop watch and ethanol solutions ranging from 0 to 5 molar in 0.2 *M* increments.

A zero MED value may not imply zero repellency because the MED test (which measures the time for water drop penetration at MED = 0) is not sensitive for soils with low degrees of repellency (Wallis *et al.* 1991). Wallis *et al.* (1991) found that soils which measured MED = 0 had repellency which significantly decreased the rate of water infiltration. However the MED test proved useful to determine the large differences in repellency of the soils in this study.

Subsamples c. 0.5 g were placed in a Leco induction furnace to determine the carbon content at each depth (Nelson and Sommers 1982). Subsamples of 10 g were used to measure soil pH in water (1:2.5 w/w) at each depth.

A Time Domain Reflectometer (TDR) (Topp and Davis 1985) was used to measure four replicates of the volumetric water content, θ from 0 - 200 mm depth at each site when the soil samples were taken in November. The TDR was also used to measure θ (0 - 200 mm depth) at each site before and after a period of rainfall in January 1991.

Discussion of Results

1. Water Repellency

The extent of soil development had a marked effect upon the repellency (MED) profiles of the 10 sites (fig. 4.13). The beach sand measured MED = 0 at all depths, however severe repellency to 200 mm depth had developed in < 130 years in the Waitarere sand. Unexpectedly, repellency declined with increasing soil age from the Waitarere sand until MED = 0 was measured from 0 - 200 mm depth for the Koputaroa sandy loam under pasture.

The Waitarere and Motuiti dune phase soils provided an opportunity to assess the effect of

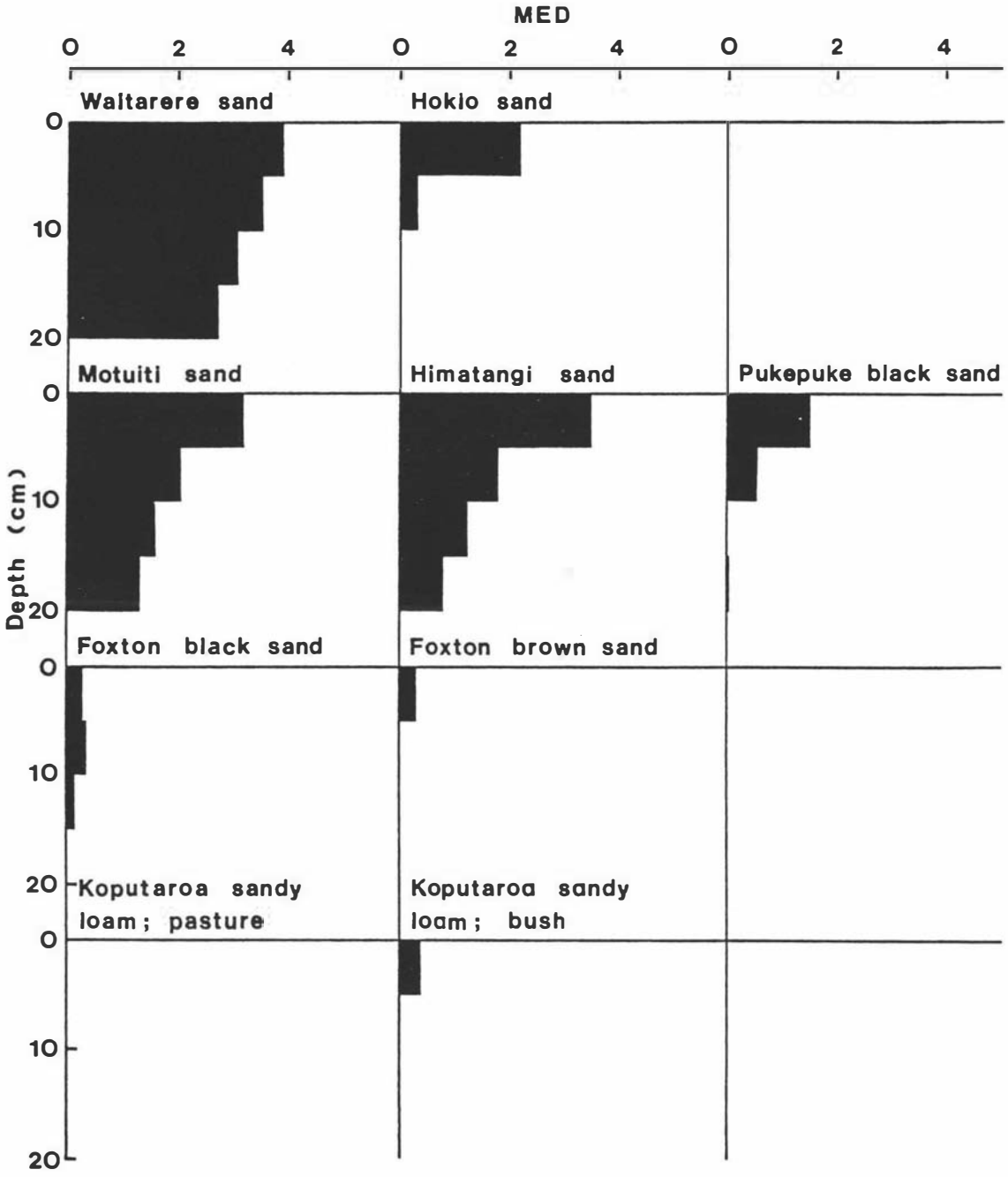


Figure 4.13. Soil water repellency (MED) profiles of nine yellow-brown sands comprising a soil development sequence.

topography upon repellency development. In both dune phases, repellency was most pronounced in the dune soils and least in the low-lying, imperfectly or poorly drained soils. Topography may affect repellency development by influencing the past and/or present vegetation. Many studies have identified a relationship between plant species and repellency (e.g. Adams *et al.* 1969; Richardson and Hole 1978; McGhie and Posner 1981) and the microorganisms associated with the plants may also be involved (Bond 1964; McGhie and Posner 1981).

Topography may also affect repellency, because repellency is expressed most strongly as a soil dries (Wallis *et al.* 1990a). Although the peaty phase of the Hokio sand measured MED 2.2 in an air-dry state, the soil is low-lying and has been found to remain consistently wet throughout summer (table 4.3). Therefore the Hokio soil would not be expected to resist water infiltration to a marked extent. The water table in the Hokio soil was found at c. 400 mm throughout the 1990/91 summer and is expected to rise to the soil surface periodically in winter. The other low-lying soil, the Pukepuke black sand was found to be dry over summer 1990/91 however the profile exhibited mottling at $<$ 300 mm depth which indicated a fluctuating water table.

The effect of bush *vs* pasture cover upon repellency severity was inconsistent between the soils of the Foxton and Koputaroa dune phases. The Foxton black sand developed under scrub and currently under pasture was found to have a greater depth of repellent soil than the Foxton brown sand which was developed, and is currently under, native bush. In contrast the Koputaroa sandy loam under pasture measured MED $=$ 0 compared to the same soil under native bush which had slight repellency at 0 - 50 mm depth. The effect of pasture *vs* bush was not directly comparable between the two dune phases because the species composition of the pasture and bush was different (table 4.1).

2. Organic Matter

Repellency was not related to the quantity of soil organic matter (fig. 4.14). Indeed, the Waitarere sand which was the most severely repellent had the lowest organic matter content measured (the carbon content of the beach sand was not determined). Bond and

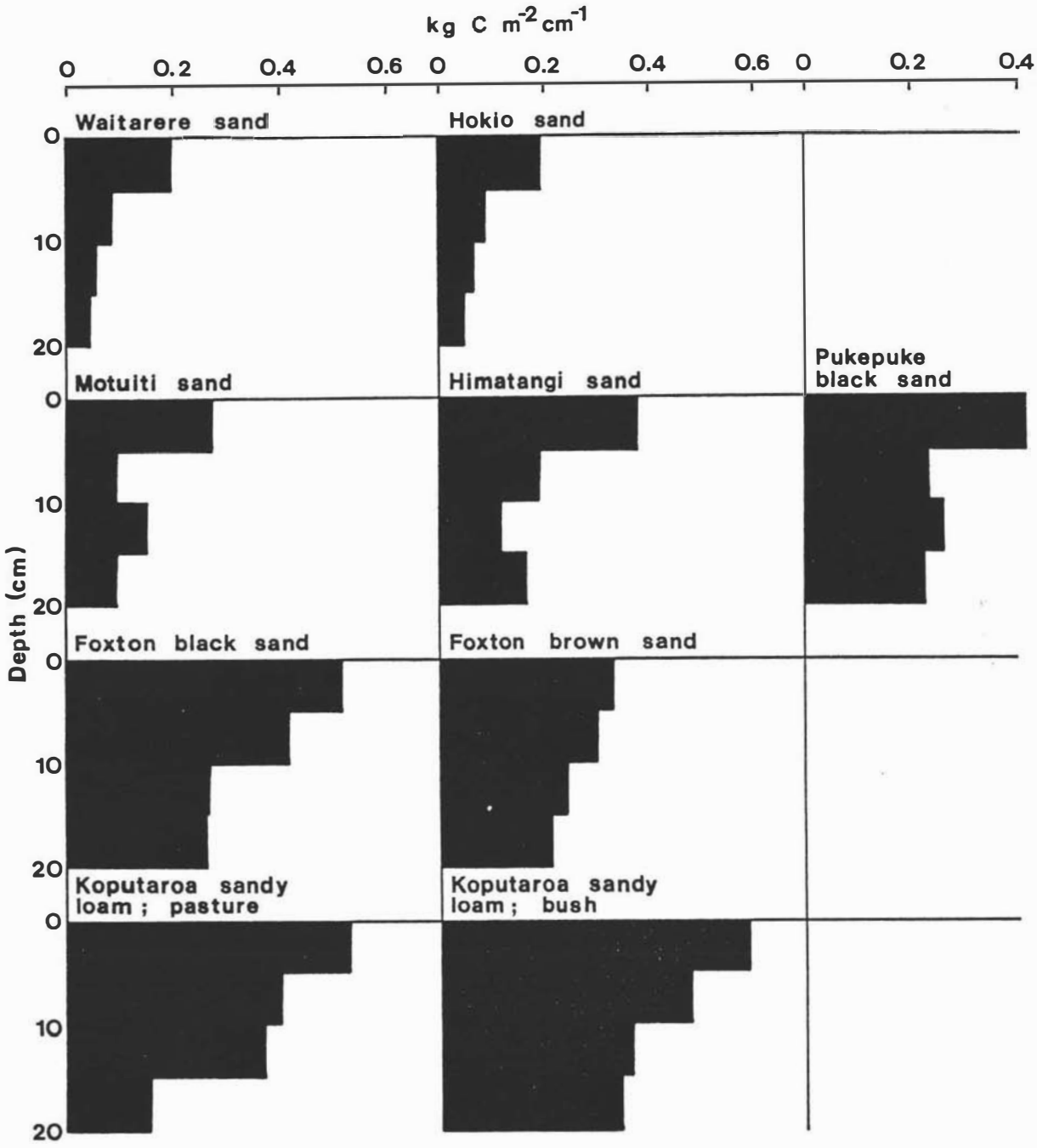


Figure 4.14. Soil carbon content (C) profiles of nine yellow-brown sands comprising a soil development sequence.

Harris (1964) found that a surprisingly small amount of organic matter (< 0.1 %) was necessary to produce severe repellency in Australian sands. DeBano *et al.* (1970) reported water repellency in sands with 0.02% organic matter. DeBano (1969a) pointed out that the total organic matter content bore no relation to the degree of repellency in Australian sands since some sands with > 5 %C were more easily wetted than others with 0.1 %C. The current results and those of DeBano (*op cit.*) suggest that only a fraction of the total organic matter is responsible for repellency.

However, the profile of repellency severity within a particular soil has been related to the quantity of organic matter present. Scholl (1975) and Singer and Ugolini (1976) reported a decrease in repellency with depth which was closely associated with decreasing organic matter. Wallis *et al.* (1990a) reported a strong correlation (R^2 = 0.79) between %C and the MED index with depth in the Himatangi sand. In this study the MED and %C profiles also follow a similar pattern in the Himatangi sand, however in the other soils MED and %C were apparently unrelated. This would further suggest that it is the nature rather than the quantity of the organic matter *per se.* which is the most important determinant of repellency.

The topsoil HA/FA ratio and FA content of five soils (Goh and Reid 1975; Goh *et al.* 1976) was compared with the average MED value for the corresponding depth of soil (table 4.2). The hypotheses detailed in the introduction would predict a proportional relationship between HA/FA and MED and an inverse relationship between FA content and MED. The soil with the highest HA/FA value (Foxton black sand) or that with the lowest FA content (Motuiti sand) would be expected to have the highest MED value. Clearly this is not the case. Furthermore the most severely repellent soil, the Waitarere sand, had the lowest-equal HA/FA value and a high FA content.

Soil pH may be an additional factor in the relationships between the HA/FA ratio and MED and the FA content and MED, as explained in the introduction. Soil of high pH, particularly pH > 6.5 at which HA is soluble, would be expected to be less repellent. However a low MED value was recorded for the most acidic Koputaroa sandy loam under bush. The Waitarere sand had a very similar pH to the Foxton black sand, therefore the HA/FA and FA results for the two soils which failed to agree with the hypotheses could

Table 4.2. Soil water repellency (MED), humic acid to fulvic acid ratio (HA/FA), fulvic acid (FA) content and pH of five yellow-brown sands.

Soil	Depth (mm)	MED	HA/FA	FA (%)	pH
Waitarere sand	50	3.85	0.7	58.9	6.19
Motuiti sand	200	2.1	2.5	18.2	6.38
Foxton black sand	200	0.21	4.5	28.1	6.16
Koputaroa sandy loam (pasture)	200	0	0.7	60.4	6.57
Koputaroa sandy loam (bush)	100	0.18	1.1	47.3	5.48

not be explained by pH. The pH of the Motuiti sand was only slightly higher than the Waitarere sand. The Koputaroa sandy loam under pasture appeared to fit all the conditions of the hypotheses for nonrepellency; low HA/FA, high proportion of FA and pH > 6.5. However, in context with the other soils, the hypotheses relating the HA/FA ratio, FA content and soil pH to repellency are not supported by the results.

3. Soil Water Content Analysis

Large differences in soil water content were measured in November 1990 when the soil samples were taken (table 4.3). In the Waitarere and Motuiti dune phases the dune soils had consistently lower soil moisture than the sand-plain soils. The severe repellency and steep relief of the dune soils would be expected to decrease infiltration and consequently the soil water content. Topographic position of the soils in relation to the water table would also increased the water content of the low-lying soils relative to the dune soils. Scotter (1989) conducted an analysis based upon soil water statics and dynamics of the Pukepuke soil which suggested that surface soil moisture would only be influenced when the water table is < 1 m deep. During summer the water table of the Pukepuke soil was > 1 m deep, however in the Hokio soil the water table was c. 400 mm from the soil surface and would be expected to influence the surface soil water content.

The effect of bush cover upon soil moisture was inconsistent between the Foxton and Koputaroa soils in November, however at later dates the soils under bush were always more moist than the same soils under pasture. The bush canopy may have produced a more humid microclimate and reduced evaporation from the soil surface. The pasture may have also had a higher transpiration rate than the plants which comprised the bush canopy.

By January 1991 the water content of all the soils had declined. In general the water contents were greatest in the oldest soils inland from the coast, presumably because the coastal summer rainfall was lower than the inland rainfall (Cowie *et al.* 1967). Despite the rainfall gradient, the soil moisture response to a period of rainfall between January 14-17, 1991 was most informative. The property owners at the Foxton brown sand and Foxton black sand sites measured 40 mm and 30 mm rainfall over the three days respectively.

Table 4.3. Water content measurements of nine yellow-brown sands.

Soil	Volumetric Water Content (θ), 0 - 200 mm Depth			Increase 14-18/1/91	
	Nov. 1990	14/1/91	18/1/91	θ	(mm)
Waitarere sand	7.2 ± 5.2[1]	3.1 ± 0.7[2]	2.2 ± 1.5[2]	-0.9	-1.8
Hokio sand, peaty phase	62.7 ± 0.7	55.4 ± 4.1	56.2 ± 6.3	0.8	1.6
Motuiti sand	17.6 ± 4.9	5.5 ± 0.2	7.1 ± 1.9	1.6	3.2
Himatangi sand	19.6 ± 5.6	5.4 ± 0.3	8.8 ± 3.4	3.4	6.7
Pukepuke black sand	25.8 ± 5.3	5.6 ± 0.2	15.0 ± 3.9	9.4	18.8
Foxton black sand	18.1 ± 4.5	7.0 ± 1.2	16.1 ± 3.3	9.1	18.2
Foxton brown sand	29.7 ± 1.7	13.5 ± 2.0	20.8 ± 3.5	7.3	14.5
Koputaroa s.l. (pasture)	36.2 ± 0.2	22.4 ± 2.4	31.9 ± 1.7	9.5	19.0
Koputaroa s.l. (forest)	35.6 ± 1.9	26.4 ± 2.6	34.0 ± 3.1	6.6	15.1

[1,2] Mean and standard deviation of 4 and 10 replicates respectively.

Unfortunately a rainfall measurement could not be obtained near the Hokio and Waitarere sites. Soil water contents were measured immediately after rainfall, so that evaporation was negligible.

In general the most severely repellent soils displayed the least increases in soil water content. The water content of the Hokio soil increased slightly while that of the Waitarere soil actually decreased, indicating that little rainfall fell near the coast and that rainfall upon the dry, severely repellent Waitarere sand ran off the soil surface and infiltrated into lower-lying, moist and therefore nonrepellent Hokio sand.

The effects of surface water redistribution were more marked in the Motuiti dune phase soils. All three soils had a very similar water content before rainfall, however the water content increase in the lowest-lying, least repellent Pukepuke soil was c. 9 times greater than that for the severely repellent Motuiti dune sand. Although the Himatangi sand measured a slightly higher surface-soil MED than the Motuiti sand, its moisture content increased by approximately double that of the dune soil. The Himatangi site was flat compared to the steep Motuiti dune site, which would have facilitated greater water infiltration.

The water content increases in the least repellent Foxton and Koputaroa soils were similar to that of the Pukepuke black sand. However, despite 30 - 40 mm measured rainfall, the water contents of the Foxton and Koputaroa soils increased by < 19 mm. The rainfall may have contributed to increased soil moisture at depth > 200 mm and the balance may be accounted for by a small amount of evaporation. Bush cover over the Foxton and Koputaroa soils also appears to have intercepted some rainfall since the moisture content increase of the forest-covered soils was c. 4 mm less than that for the pasture-covered soils. Spatial variability in rainfall is unlikely to account for the difference between the Koputaroa soils, because the bush and pasture sites were < 100 m apart. However rainfall variability may have been significant between the Foxton sites, which were 2.3 km apart.

The most severely repellent soils had the greatest variation in water content after rainfall

(fig. 4.15). The Hokio soil had a high water content and would not express repellency, therefore the coefficient of variation (C.V.) was low. Before rainfall the soil water content at each site was reasonably uniform (C.V. < 21 %) however after rainfall the C.V. of all soils other than the Koputaroa sandy loam under pasture increased. High spatial variability of the moisture content in repellent soils has been reported by numerous authors (e.g. Bond 1964; Hendrickx *et al.* 1988a) and may be due to the pattern of present and/or past vegetation and associated soil microorganisms.

Conclusions

Severe repellency developed after < 130 y in a yellow-brown sand with limited organic carbon. Repellency severity declined in soils of increasing age, suggesting that the nature rather than the quantity of organic matter in soil is the most important determinant of repellency development.

The dune soils were more repellent than the sand plain soils of equal age. Soil topographic position affects plant and soil microorganism populations which comprise the origin of the hydrophobic organic material responsible for repellency. Also, topography affects soil moisture, which in turn affects the expression of repellency.

Repellency development did not appear to be related to the current vegetation cover of either bush or pasture in the Foxton and Koputaroa dune phases, however it is important to note that the composition of the bush and pasture in the two dune phases differed. Repellency may be related to particular past or present species of plants and associated microorganisms, which would help to explain the spatial variability of water content measured in the repellent soils.

Repellency severity was not related to the HA/FA ratio or FA content as proposed by a number of authors. Introducing the pH factor, which affects HA and FA solubility, did not improve the relationships. HA and FA are arbitrary organic fractions based upon extraction conditions and comprise many compounds. Identification of the specific compound(s) responsible for repellency would be more useful, and is the subject of

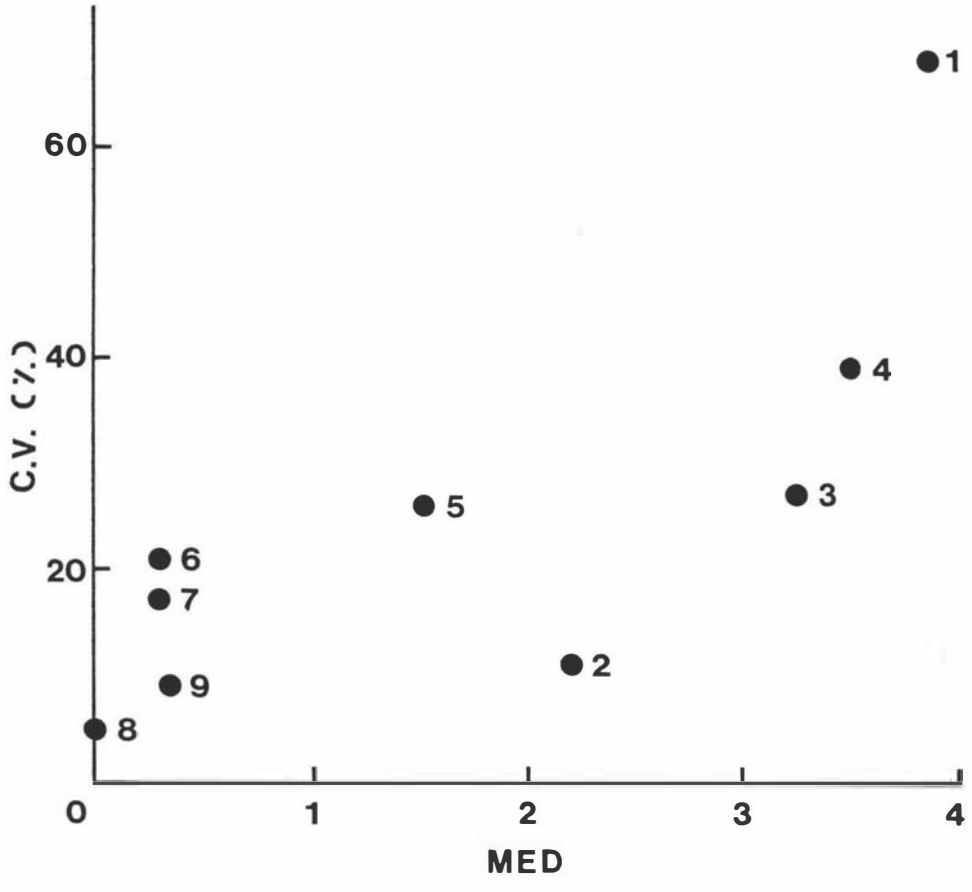


Figure 4.15. Post-rainfall coefficient of variation (C.V.) of volumetric soil water content, θ (0 - 200 mm depth) versus soil water repellency, MED (0 - 50 mm depth) of nine yellow-brown sands comprising a soil development sequence. 1 = Waitarere sand; 2 = Hokio sand, peaty phase; 3 = Motuiti sand; 4 = Himatangi sand; 5 = Pukepuke black sand; 6 = Foxton black sand; 7 = Foxton brown sand; 8 = Koputaroa sandy loam (pasture); 9 = Koputaroa sandy loam (bush).

ongoing research.

Acknowledgements

The authors are grateful to the property owners at each site for their cooperation and to Mr. I. Furkert for his technical assistance.

4.2 EXTRACTION OF THE ORGANIC FRACTION RESPONSIBLE FOR WATER REPELLENCY IN A DEVELOPMENT SEQUENCE OF YELLOW-BROWN SANDS

Introduction

It has been recognised for some time that repellency is caused by hydrophobic organic compounds which may be in intimate contact with soil surfaces (Chapter 1, section IV.A). The composition of these compounds and their sources has been the topic of some debate (Chapter 1, section IV.C). Investigations of the origin of the organic matter which gives rise to repellency and the role of microorganisms in repellent soils were beyond the scope of this study. To date no one in New Zealand has attempted to identify the compound(s) responsible for repellency. Characterising the chemical nature of the compound(s) will be important for the improved understanding of the repellency phenomena.

Ma'shum *et al.* (1988) found that an 8 h soxhlet reflux extraction with *iso*-propanol and 15.7 M ammonia (7:3 v/v) removed organic materials responsible for water repellency in a range of repellent Australian soils. After extraction the soils were nonrepellent and the extracted materials restored water repellency of acid-washed or ignited sands to levels comparable to the original, repellent soils. They then used spectroscopic and chromatographic examinations of the extract to identify compounds responsible for water repellency.

The extraction technique of Ma'shum *et al.* (1988) were employed upon the soils of the development sequence described above.

The purpose of this research was to:

(a) determine the organic compound(s) responsible for repellency in a development sequence of yellow-brown sands;

(b) compare the compound(s) with those found responsible for repellency in South Australian soils;

(c) try to establish the correlation between the content of the organic compound(s) and

the severity of repellency.

The results of this section are preliminary, and include a limited number of soils from the development sequence. Further work is ongoing with the full range of soils and additional analytical techniques.

Materials and Methods

Duplicate subsamples of 10 g were taken from the 0 - 50 mm depth soil of four yellow-brown sands described above and listed in table 4.4. The subsamples were extracted with 150 ml *iso*-propanol/15.7 M ammonia (7:3 v/v) using a Soxhlet apparatus (Ma'shum *et al.* 1988). The extracted soils were air-dried in a fume cupboard and then oven-dried at 105 °C. The repellency of each soil after extraction was measured with the MED technique as described in the above paper (section 4.1). The extracts were evaporated to dryness in a fume hood for further analysis.

Infrared spectra of the Himatangi sand extract was obtained using discs with a concentration of 1 mg material in 180 mg KBR. The spectra was recorded using a Pye Unicam SP3-300 infrared spectrophotometer. For ^{13}C-NMR analysis samples of the extracted material from the Himatangi sand were dissolved in $CDCl_3$ to give concentrations of approximately 100 mg ml^{-1}. The ^{13}C-NMR spectra were recorded on a JEOL GX270 Fourier transform NMR spectrometer operating at a frequency of 67.9 MHz at an ambient probe temperature of 18 °C. Approximately 40 K acquisitions were accumulated using a spectral width of 16 000 Hz and a pulse delay of 2 s.

Results and Discussion

All four soils had MED = 0 following extraction (Table 4.4). The successful extraction implies that the repellent compounds were not covalently bound to soil surfaces. Ma'shum *et al.* (1988) found that *iso*-propanol/ammonia was the only one of 8 extractants tested which reduced the MED value of a repellent sand from 3.5 to 0. There was no relationship between amount of material extracted and either measurements of the quantity

Table 4.4. MED values of four yellow-brown sands (0 - 50 mm depth) before and after extraction with an *iso*-propanol/ammonia mixture, and the amount of material extracted. Also shown for comparison is the carbon content of the original soil.

Soil	Original MED	MED after extraction	Amount extracted (kg m^{-2} cm^{-1})	Carbon content (kg m^{-2} cm^{-1})	Proportion (extract: total organic matter)[A]
Waitarere sand	3.85	0	0.088	0.199	25 %
Hokio sand (peaty)	2.20	0	0.068	0.186	21 %
Motuiti sand	3.20	0	0.200	0.275	42 %
Himatangi sand	3.50	0	0.269	0.378	41 %

[A] To obtain figures in this column a ratio of % carbon to % organic matter of 0.58 has been assumed.

of carbon or initial soil MED (table 4.4). Likewise Ma'shum *et al.* (1988) found no relationships, and they concluded that some components of the extracts were much more effective at inducing water repellency than others. Interestingly, they suggested that not only the nature and concentration of the hydrophobic components need to be studied, but also the nature and concentration of the hydrophylic fraction.

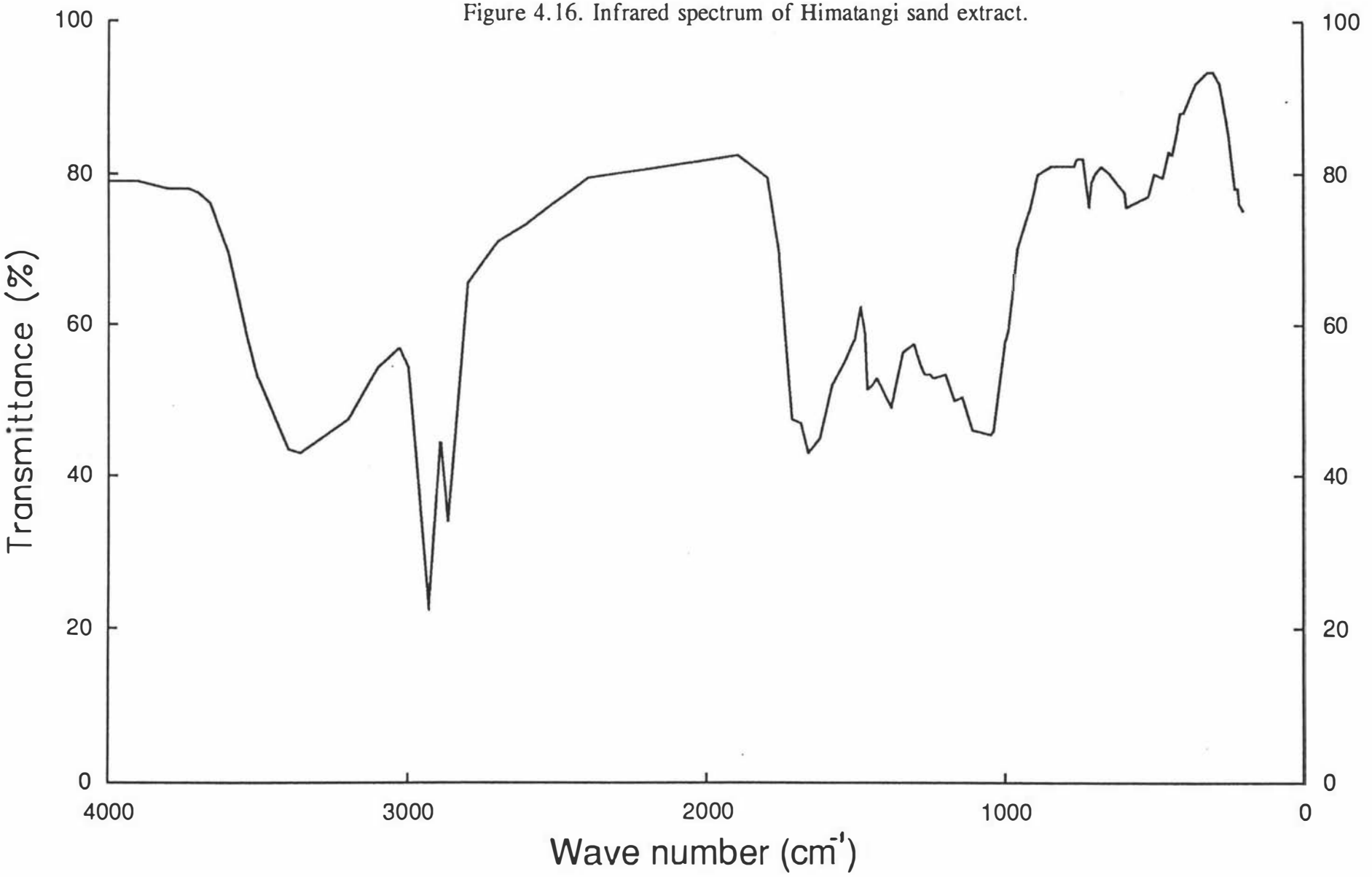
The amounts of material extracted from the four soils (table 4.4) were considerably higher than that removed from six Australian soils (Ma'shum *et al.* 1988), except for one case where they extracted a soil developed under brown mallet trees. In the New Zealand sands, a reasonable proportion of the total organic matter was extracted with *iso*-propanol/ammonia (table 4.4).

The features of the infrared spectra of the Himatangi sand (fig. 4.16) were remarkably similar to spectra from sand grains of repellent golf greens (Miller and Wilkinson 1977), Western Australian hydrophobic plant litter (McGhie 1980), material extracted from repellent Italian soils (Giovannini and Lucchesi 1984), and from a South Australian repellent soil (Ma'shum *et al.* 1988). The dominant features of figure 4.16, which are shared with the spectrum presented by Ma'shum *et al.* (1988) and others, include the C-H stretching at 2917 cm^{-1}, bending at 1460 cm^{-1} and rocking at 720 cm^{-1}. These frequencies are characteristic of extended paraffinic chains.

Using a diffuse reflectance accessory for infrared spectroscopy Ma'shum *et al.* (1988) found a correlation between absorbance at a frequency of 2917 cm^{-1} and the concentration of soil lipids added to acid-washed sand. Determination of such a relationship in the yellow-brown sands would be an obvious avenue for future research.

The ^{13}C-NMR spectra of the Himatangi sand extracts (fig. 4.17) were similar to that published by Ma'shum *et al.* (1988), showing large polymethylene resonance at 29.7 ppm, along with CH_2-CH_2-CH_3, -CH_2-CH_3 and -CH_3 resonances at 31.9, 22.6 and 14.1 ppm respectively. The carbonyl resonances at 173.9 ppm are typical of acids and esters, which are more obvious in the Himatangi sand spectrum than that of Ma'shum *et al.* (1988), where they were barely detectable above background noise. In Ma'shum *et al.*'s (1988)

Figure 4.16. Infrared spectrum of Himatangi sand extract.



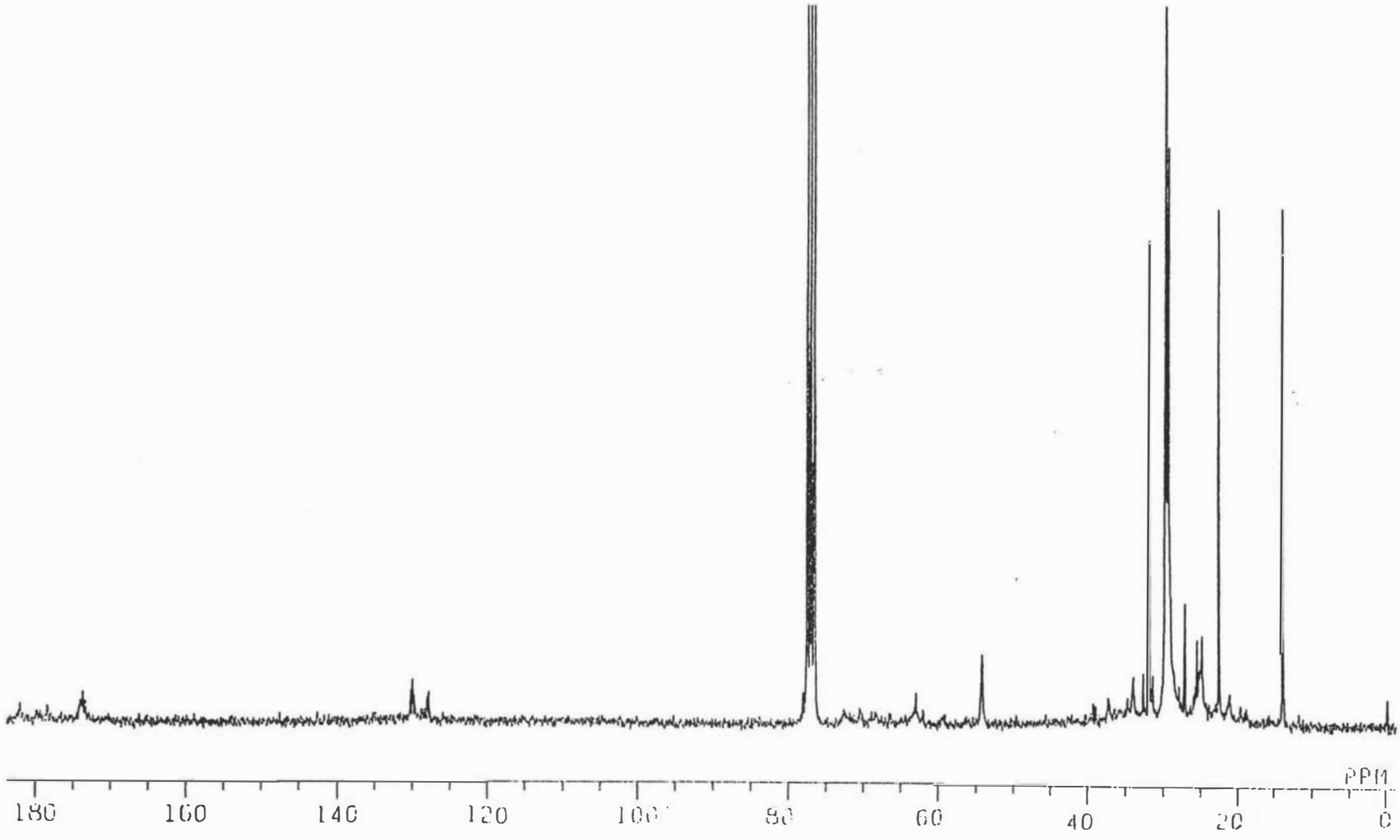


Figure 4.17. ^{13}C NMR spectrum of Himatangi sand extract. The sharp triplet centred at 77.0 ppm is caused by the $CDCl_3$ solvent.

study only a sublimate of the soil lipids showed carbonyl resonance. Resonance at frequencies c. 128 ppm were probably due to unsaturated carbon chains such as benzene substituted with groups such as $COCH_3$, $COOCH_3$ and CHO.

Ma'shum *et al.* (1988) was in the envious position of having access to gas chromatograph-mass spectrometric (GC/MS) equipment. With this he was able to determine that 1 - 18 % of the hydrophobic carbon extracted by *iso*-propanol/ammonia was present as combined and uncombined long-chain fatty acids with 16 - 32 carbon atoms. Unfortunately for this study, financial constraints prohibited GC/MS analysis of extracts to identify the fatty acid component.

Conclusions

Although this study to identify the compound(s) responsible for repellency in the yellow-brown sands has been a tentative attempt, a number of important conclusions can be drawn.

Firstly, the *iso*-propanol/ammonia mixture has been shown to be very effective for extraction of the material responsible for repellency.

Secondly, the amount of material extracted from the yellow-brown sands was considerably greater than that removed from Australian sands. This may suggest that in general repellency is a greater problem in the New Zealand soils, which is supported in part by larger MED values of the New Zealand soils. Unfortunately there was no close relationship between the quantity of extract and the severity of repellency expression. The inference is that only a specific fraction of the extract plays a major role in repellency development.

Thirdly, spectroscopic examinations of the material extracted from a yellow-brown sand were remarkably similar to those reported by others, and in particular Ma'shum *et al.* (1988). Although much further research is required it would appear that repellency of one yellow-brown sand is caused by molecules with extensive polymethylene chains,

substituted aromatics, esters and fatty acids.

Most organic acids are transient, their fate being dependent upon a number of soil properties such as moisture content. It may be that certain organic acids are produced and assimilated on the micro scale, because of spatial and temporal variability in microorganism populations and plant species. Better appreciation of the consequently dynamic nature of the repellent soil particle coating may be the key to improved understanding of the temporal and spatial variability of repellency.

CHAPTER FIVE: INTRINSIC SORPTIVITY AS AN INDEX FOR WATER REPELLENCY MEASUREMENT

5.0 INTRODUCTION

Development of the 'Repellency Index' (RI) based upon the intrinsic sorptivity of the soil medium was detailed in Chapter 1. Tillman *et al.* (1989) measured the RI of a moist sandy loam which appeared to absorb water 'normally'. They called for further evaluation of the RI technique, which needed to be compared with existing methods of water repellency measurement. Changes in soil sorptivity to water and ethanol with time of measurement also needed to be quantified on a range of soils. Furthermore, the suggestion of Tillman *et al.* (1989) that water repellency may be much more widespread than is commonly thought warranted investigation.

5.1 AN EVALUATION OF THE INTRINSIC SORPTIVITY WATER REPELLENCY INDEX ON A RANGE OF NEW ZEALAND SOILS

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Abstract

Undisturbed cores were removed from the surface of 14 New Zealand soils with a wide range of textures. The sorptivity to ethanol and water was measured with a 'sorptivity tube' to determine the repellency index (RI) of each soil. Texture and gravimetric water content were measured, and the water drop penetration time (WDPT) and molarity of ethanol droplet (MED) tests for water repellency were conducted on the soils.

The RI measured all soils water repellent (RI > 1.95) at field moisture conditions, and was more sensitive than the WDPT or MED tests. The RI was used to demonstrate that water repellency reduced short-time water infiltration of all soils by approximately an order of magnitude. Actual and 'potential' infiltration was then compared with rainfall and irrigation intensities. This illustrated the hydrological significance of the phenomenon, even in soils which appeared to wet normally (low WDPT).

In all soils the curves of cumulative infiltration versus the square root of time for both water and ethanol stayed linear long enough for sorptivity evaluation. However at longer times the slope of the curve tended to increase for water sorption in the more repellent soils, but decreased consistently for ethanol.

Introduction

Water repellent soils exhibit hydrophobic properties when dry, resisting or retarding water infiltration into the soil matrix (Brandt 1969a). Such soils have been reported in many countries (DeBano and Letey 1969), and may occupy large areas, such as the sandy soils of South and Western Australia (Ma'shum *et al.* 1988; McGhie, 1987). However severe water repellency is relatively uncommon, and hence the condition is generally regarded as interesting but inconsequential. Indeed, the assumption of non-water repellent behaviour is the norm in soil physics (Philip, 1969).

Recently, Tillman *et al.* (1989) reported significant water repellency in a relatively moist, fine-textured soil which appeared to absorb water normally. They concurred with Marshall and Holmes' (1979) speculation, that water repellency 'probably affect(s) the advance of water quite commonly during the wetting of dry soil, although the effects are easily observed only in severe cases'.

Tillman *et al.* (1989) developed a new technique for measurement of soil water repellency based upon the intrinsic sorptivity of the medium. The purposes of this paper are as follows:

1. To use the intrinsic sorptivity repellency index (RI) to determine if water repellency is a widespread condition in New Zealand soils;
2. To compare the RI with existing techniques for water repellency measurement;
3. To evaluate any changes in water and ethanol infiltration over time for each soil;
4. To evaluate the time period for RI measurement on a range of soils.

Materials and Methods

The Repellency Index (RI)

Fourteen soils were evaluated from the Manawatu, Central Otago and Canterbury regions of New Zealand (Table 5.1). The soils were selected for their agricultural and

Table 5.1. Soils used for the Repellency Index, Water Drop Penetration Time and Molarity of Ethanol Droplet water repellency tests.

Region and Soil Type	US Taxonomic Classification	Landscape position	Vegetation Cover
Manawatu			
Himatangi sand	Aquic Udipsamment	Dry sand plains	Pasture[B]
Manawatu fine sandy loam	Dystric Fluventic Eutrochrept	Low terrace	Pasture[B]
Tokomaru silt loam	Typic Fragiaqualf	Marine bench	Pasture[B]
Motua humic clay[A]	Fluvaquentic Haplaquoll	Low terrace	Maize[C]
Central Otago			
Conroy fine sandy loam	Lithic Ustollic Camborthid	Foothills	Apricots
Waenga fine sandy loam	Ustollic Camborthid	Young fans	Nectarines
Molyneux fine sandy loam	Ustic Torriorthent	Intermediate terrace	Nectarines
Earnscleugh loam	Fluventic Ustochrept	Low terraces	Apricots
Manuherikia loam	Ustollic Camborthid	Low terraces & lowest intermediate terrace	Apples
Canterbury			
Hatfield silt loam	Udic Ustochrept	Fans & high terraces	Lentils[D]
Chertsey silt loam	Udic Ustochrept	Fans & high terraces	Barley[D]
Templeton loam	Fluventic Haplustoll	Fans	Barley[D]
Wakanui clay loam	Udic Ustochrept	Depressions in low terraces	Barley[D]
Waimakariri loam	Fluventic Ustochrept	Low terrace	Tall fescue

[A] Mapped as Kairanga silt loam.
[B] Ryegrass/clover.
[C] Standing, poor growth area.
[D] Cropped.

horticultural importance, with a wide range of textures from three climatic zones. Water repellency of the Himatangi sand has been reported (Wallis *et al.* 1990 a,b). The Himatangi sand is described by Cowie *et al.* (1967); the other Manawatu soils by Cowie (1978); the Central Otago soils by McCraw (1964) and the Canterbury soils by Bear *et al.* (1967).

Any vegetation on the sites was trimmed to < 5 mm height with scissors. The Central Otago soils were removed from orchard herbicide strips. Pairs of 50 mm x 50 mm cylindrical corers were driven into the surface of each soil, leaving approximately 5 mm space at the top of each corer. The cores were lifted carefully with a spade, trimmed flush at the base with a knife, placed in plastic bags and transported to the laboratory in an insulated container. Cores were removed from the Himatangi sand in September 1989 and February 1990. Cores were removed from all other soils in February 1990.

Initial weights were recorded for gravimetric water content analysis. A measured quantity of non-repellent sand (muffle-furnaced Himatangi sand) was spread on the surface of each soil core to provide a contact medium *c.* 5 mm deep. A 'sorptivity tube' similar to that described by Clothier and White (1981) was used to measure the infiltration rate of water into one member of each pair of cores, and of 95% ethanol into the other. As for the technique outlined by Tillman *et al*, 1989, the surface pressure potential of water and ethanol was imposed by air entry into a 0.66 mm internal diameter needle. Glass was used to construct the sorptivity tube because acrylic deteriorated following contact with ethanol.

Cumulative infiltration (I) was plotted against the square root of time ($t^{½}$), and sorptivity (S) of water and ethanol measured as the slope of the curve over short time when I was proportion to $t^{½}$. The intrinsic sorptivity repellency index (RI) was calculated as described by Tillman *et al.* (1989) using the equation:

$$RI = 1.95\ (S_E/S_W), \qquad (1)$$

where S_E and S_W are determinations of sorptivity of ethanol and water respectively. The mean and standard error of each soil RI was calculated using the mean and standard error of the S_W and S_E values (Barford 1967).

An RI of 1.0 was measured in initially dry acid-washed sand by Tillman *et al.* (1989). Due to the miscible behaviour of the infiltrating ethanol or water and the soil solution, RI values up to 1.95 are theoretically possible in initially moist, non-repellent soil. As noted by Tillman *et al.* (1989), the RI method is only applicable in non-swelling soils with a water-stable structure. In initially dry swelling soils, exothermic reactions and structural changes during wetting would affect the soil sorptivity to water and ethanol differentially, regardless of water repellency. All the soils evaluated in this study had stable structure and montmorillonite clay content $< 10\%$.

Soil water infiltration from 0-5 minutes was calculated from the sorptivity tube data. Infiltration into the contact sand, typically over the 0-10 s time period, was substracted from the total infiltration at 5 minutes. The 'potential' infiltration if each soil was non-repellent was then calculated as the product of the actual rate and RI.

Cores were air-dried to allow ethanol evaporation, oven-dried and weighed to allow calculation of gravimetric water content. Sub-samples of *c.* 10 g were removed for pipette particle size analysis (Folk 1974) and subsequent soil texture classification.

WDPT and MED Water Repellency Tests

The Water Drop Penetration Time (WDPT) of each soil was measured by placing a *c.* 5 g subsample of air-dry soil in a petri-dish, lightly compacting the surface and placing a standard sized water drop on the surface with a dropper. The time for penetration of the water drop was recorded (Letey, 1969). The Motua humic clay WDPT was not measured.

Subsamples of *c.* 5 g were also evaluated for water repellency by the Molarity of Ethanol Droplet (MED) test, first proposed by Watson and Letey (1970) and developed by King (1981). The MED test measures the molarity of an aqueous ethanol droplet required for soil infiltration within 10s. Ethanol lowers the liquid surface tension, enabling infiltration regardless of the soil contact angle. King (1981) provided the following guidelines for interpretation of MED and WDPT values: MED $= 0$, WDPT $\leq$ 7s, non-significant

repellency; MED < 1, 8s ≤ WDPT ≤ 53s, low repellency; MED 1.0-2.2, WDPT > 53s, moderate repellency; MED > 2.2, WDPT undefined, severe repellency.

Results

The Repellency Index (RI)

The repellency index showed that all soils were water repellent (RI > 1.95) at field moisture content (Table 5.2). The RI of dry Himatangi sand, which the MED test classifies as 'severely repellent' (Wallis *et al.* 1990a), approached 100. Sands are considered prone to severe water repellency because the low specific surface is readily coated with hydrophobic organic material (DeBano *et al.* 1970). Wallis *et al.* (1990a) reported a strong correlation between carbon content and MED with depth in the Himatangi sand.

From this study it is evident that water repellency is not restricted to sands. RI values of the other soils ranged from 3 to 46. Of particular interest is the Motua humic clay, a strongly aggregated soil with a carbon content of 7-8% which has a high RI and MED. McGhie and Posner (1980) reported water repellency in a strongly aggregated West Australian clay, and suggested that hydrophobic organic material coated the soil aggregates. We propose a similar interaction between soil structure and organic matter as the water repellency mechanism in the Motua humic clay.

As illustrated by the values for Himatangi sand, the RI is dependent upon antecedent moisture content and is expected to increase as soil dries (Tillman *et al.* 1989). Wallis *et al.* (1990a) used the MED test to show that water repellency declined as moisture content of the Himatangi sand increased.

To assess the hydrological significance of water repellency in each soil we used the RI to compare actual and 'potential' short-time water infiltration (Table 5.3). Actual and 'potential' water infiltration may be compared with rainfall intensity and irrigation application rates.

Table 5.2. Repellency Index (RI) determinations on n samples at w gravimetric water content with water sorptivity, S_w. Molarity of Ethanol Droplet (MED) and Water Drop Penetration Time (WDPT) determined on air-dry soil samples.

Region and soil type	Repellency Index Cores				MED	WDPT
	n	w	S_w (mm min$^{-½}$)	RI		(s)
Manawatu						
Himatangi sand	5	0.04	0.4 ± 0.1[A]	93 ± 26[A]	2.7	> 3600
Himatangi sand	5	0.26	2.5 ± 0.6	7 ± 2	2.7	> 3600
Manawatu f.s.l.	3	0.19	1.1 ± 0.2	25 ± 5	0	< 0
Tokomaru silt loam	4	0.23	1.1 ± 0.1	29 ± 4	0	< 0
Motua humic clay	6	0.17	0.6 ± 0.1	46 ± 10	2.3	-
Central Otago						
Conroy f.s.l.	5	0.03	1.6 ± 0.2	14 ± 2	0	2.3 ± 1.3[A]
Waenga f.s.l.	5	0.10	1.3 ± 0.2	13 ± 3	0	< 1
Molyneux f.s.l.	3	0.06	2.2 ± 0.4	7 ± 2	0	< 1
Earnscleugh loam	5	0.08	0.8 ± 0.1	34 ± 6	0.1	10.1 ± 4.3
Manuherikia loam	5	0.19	0.5 ± 0.1	23 ± 5	0	1.6 ± 0.6
Canterbury						
Hatfield silt loam	4	0.08	5.1 ± 0.2	3 ± 0.4	0	< 1
Chertsey silt loam	4	0.12	1.6 ± 0.5	13 ± 4	0	< 1
Templeton silt loam	4	0.11	1.7 ± 0.2	8 ± 1	0	< 1
Wakanui clay loam	5	0.09	1.1 ± 0.1	10 ± 3	0	8.3 ± 2.6
Waimakariri loam	5	0.05	2.5 ± 0.4	4 ± 1	0	4.5 ± 0.6

[A] Mean and standard error

Table 5.3. Cumulative water infiltration over 5 minutes and 'potential' infiltration if each soil were non-repellent.

Region and soil type	5-minute infiltration (mm)	
	Actual	'Potential'
Manawatu		
Himatangi sand (dry)	0.8 ± 0.2[A]	74
Himatangi sand (moist)	5.6 ± 1.2	39
Manawatu f.s.l.	2.1 ± 0.3	53
Tokomaru silt loam	2.0 ± 0.3	58
Motua humic clay	0.8 ± 0.3	37
Central Otago		
Conroy f.s.l.	3.5 ± 0.7	49
Waenga f.s.l.	2.8 ± 0.4	36
Molyneux f.s.l.	3.0 ± 0.6	21
Earnscleugh loam	1.9 ± 0.2	65
Manuherikia loam	1.1 ± 0.1	25
Canterbury		
Hatfield silt loam	6.9 ± 0.2	21
Chertsey silt loam	3.2 ± 0.6	42
Templeton loam	2.3 ± 0.2	18
Wakanui clay loam	1.7 ± 0.1	17
Waimakariri loam	3.9 ± 0.6	16

[A] Mean and standard error

Five-minute rainfall of 5 year return interval may reach 4 mm in Central Otago, 5 mm in Canterbury and 12 mm in the Manawatu (Tomlinson 1980). During such events, the likelihood of water runoff from all soils except the Hatfield silt loam is increased by water repellency, especially when the soils are dry. This may explain the common observation of enhanced runoff during summer storms.

Travelling boom and big-gun irrigators used in New Zealand often have application rates > 100 mm h^{-1} (Cook 1983; John *et al.* 1985). Water repellency of all soils is likely to increase irrigation runoff and reduce irrigation efficiency, particularly when systems with high application rates are used.

Tillman *et al.* (1989) made the distinction between 'critical repellency', when free water is prevented from entering dry soil pores, and 'subcritical repellency' when the soil wets spontaneously but the rate of wetting is reduced. All soils other than the Motua and Himatangi wet spontaneously (WDPT < 1 s) or rapidly (WDPT < 11 s). Since water repellency reduced the short-time infiltration of all soils by approximately an order of magnitude we suggest that the 'critical' *vs* 'sub-critical' distinction based upon wetting time should be avoided and the MED severity scale of King (1981) should be reviewed.

The RI versus *WDPT and MED Tests*

The relationship between MED, WDPT and RI is demonstrated in Table 5.2. The Himatangi sand and Motua humic clay are severely repellent (MED > 2.2) with RI values of 93 and 46 respectively. The Earnscleugh loam measured low MED water repellency at RI $= 34$ and all other soils had MED $= 0$ but RI > 1.95. The WDPT of air-dry Himatangi sand exceeded one hour. When WDPT was measured on moist Himatangi sand, water drops penetrated in < 1 s (Wallis 1987). WDPT measured < 11s on the other soils. By definition, WDPT < 10s for MED $= 0$. The RI is therefore more sensitive than the WDPT and MED tests. A further advantage of the RI over the MED and WDPT tests is that it measures a physically significant parameter.

Although we measured RI at field moisture content, measurement at a standard matric

potential, such as air-dry, would also have been useful. It would have been possible to correlate RI with the WDPT and MED tests, however the spatial and temporal variability of water repellency (Wallis *et al.* 1990a) may limit the validity of such correlations. It would be better to measure the RI directly. We suggest that air-dry RI values are used if a measurement independent of soil water content is needed, such as for wetting agent evaluation (Wallis *et al.* 1990b).

Change in Infiltration with Time

Tillman *et al.* (1989) measured water and ethanol absorption into a horizontal tube of sieved Manawatu fine sandy loam incubated at $w = 0.12$. They found that the slope of the I *vs* $t^{½}$ curve for water increased with time, and that for ethanol decreased with time. DeBano (1969a) pointed out that, in contrast to 'wettable' soils, the infiltration rate in water repellent soils increases with time.

In the more repellent soils we studied, plots of I *vs* $t^{½}$ for water tended to increase with time except in the Motua humic clay. An example of I *vs* $t^{½}$ for dry Himatangi sand is given in Fig. 5.1. The Waenga soil (Fig. 5.1) provides an example of linear I *vs* $t^{½}$ behaviour over the entire period of measurement, which occurred in 9% of the samples. One half of the soils displayed a decrease in the slope of the I *vs* $t^{½}$ curve with time, such as the Hatfield silt loam (Fig. 5.1). Such behaviour may be due to gradations in pore size distribution, antecedent moisture content or water repellency over the depth of the core sample. However, no obvious surface crusts or changes in structure with depth were observed.

Wallis *et al.* (1990a) reported near-linear I *vs* t behaviour for water infiltration into severely repellent Himatangi sand with a + 10 mm positive head disc permeameter (Perroux and White 1988). A plot of this data revealed that the I *vs* $t^{½}$ slope increased with time, but there were no observations at times < 1 min, when linear I *vs* $t^{½}$ behaviour may have occurred.

Examples of ethanol infiltration behaviour are given in Fig. 5.2. The slope of the I *vs* $t^{½}$

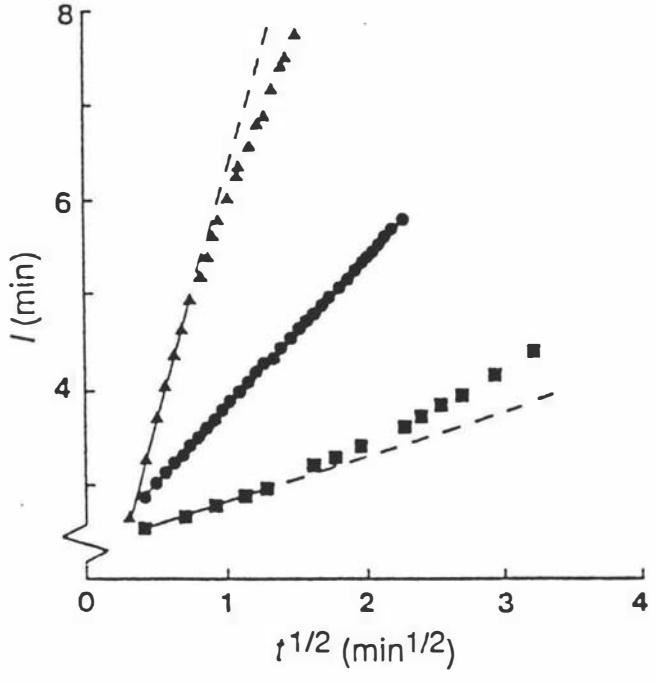


Figure 5.1. Cumulative water infiltration (I) versus the square root of time ($t^{1/2}$) for soil cores of Hatfield silt loam (▲), Waenga fine sandy loam (●) and dry Himatangi sand (■). Lines were fitted by eye to the linear part of the data, indicated by the solid line segment.

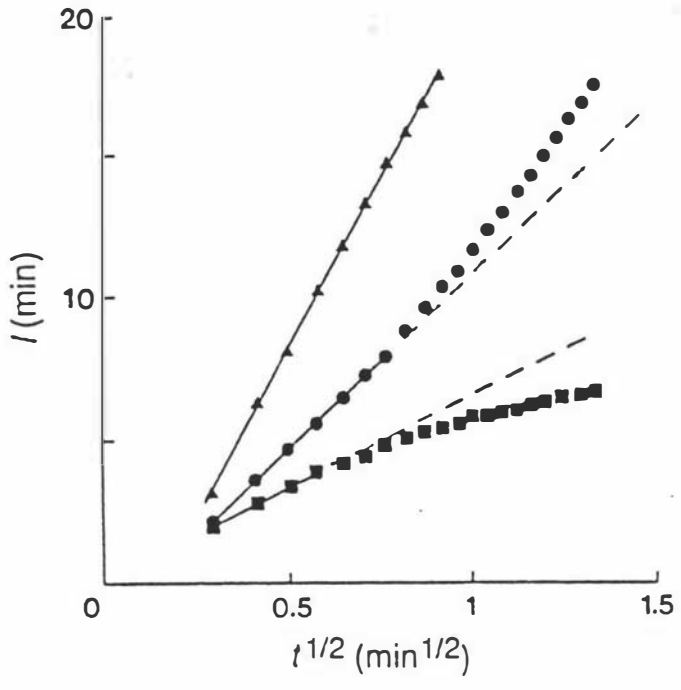


Figure 5.2. Cumulative ethanol infiltration (I) versus the square root of time ($t^{½}$) for soil cores of dry Himatangi sand (▲), Conroy fine sandy loam (●) and Manuherikia loam (■). Lines were fitted by eye to the linear part of the data, indicated by the solid line segment.

curve for ethanol decreased with time in 78% of the samples. In many instances the slope decreased markedly, such as the Manuherikia example given. Tillman *et al.* (1989) suggested that this behaviour is due to resident water pushed ahead of the ethanol being slowed by water repellent soil. If this is the mechanism slowing ethanol infiltration over time, it was not restricted to soils with high water content. Linear I *vs* $t^{½}$ behaviour over the entire period of measurement occurred infrequently (7% of samples). An increase in the I *vs* $t^{½}$ slope for ethanol occured in 15% of samples. This behaviour may have been due to the gradations within the core samples suggested above.

Time Period for RI Measurement

Tillman *et al* (1989) measured the RI of moist Manawatu fine sandy loam in the field (gravimetric water content, $w = 0.24$). They measured a linear relationship between cumulative infiltration (I) and square-root time ($t^{½}$) for water over *c.* 27 min and for ethanol over *c.* 7 min. We wished to evaluate the time period for linear behaviour ($I \alpha t^{½}$) of water and ethanol infiltration into a range of soils (Table 5.4). Water infiltration was normally measured over *c.* 5 min and ethanol infiltration over 1-5 min depending upon the speed of infiltration. A number of soils displayed linear behaviour over the entire period of measurement. For these soils the mean time period of linear behaviour is reported as a minimum value.

The time of linear behaviour for water and ethanol infiltration in the Himatangi sand decreased when soil moisture content increased. In contrast, the time of linear behaviour for water and ethanol infiltration in the Manawatu f.s.l. was lower at $w = 0.19$ than the times measured by Tillman *et al.* (1989) at $w = 0.24$. Regardless of moisture content, linear behaviour in all soils lasted long enough for S_W and S_E to be calculated. The time for S_E calculation ranged from 0.3 to 1.0 min and the time for S_W calculation ranged from 0.7 to 9.4 minutes. The soils with higher RI values tended to have longer times for S_W calculation.

Table 5.4. Time period over which cumulative infiltration (I) was proportional to the square root of time ($t^{½}$) for water and ethanol infiltration.

Region and soil type	Time (min) over which $I \alpha t^{½}$	
	Water infiltration	Ethanol infiltration
Manawatu		
Himatangi sand (dry)	9.4 ± 1.9[A]	> 1.0
Himatangi sand (moist)	> 2.8	0.5 ± 0.1[A]
Manawatu f.s.l.	4.7 ± 1.6	> 0.3
Tokomaru silt loam	> 2.9	0.4 ± 0
Motua humic clay	0.9 ± 0.1	1.0 ± 0.2
Central Otago		
Conroy f.s.l.	> 0.9	0.7 ± 0.1
Waenga f.s.l.	> 1.9	0.9 ± 0.2
Molyneux f.s.l.	> 1.1	1.0 ± 0.3
Earnscleugh loam	1.4 ± 0.3	0.6 ± 0.1
Manuherikia loam	1.8 ± 0.4	0.7 ± 0.1
Canterbury		
Hatfield silt loam	0.7 ± 0.1	0.6 ± 0.04
Chertsey silt loam	1.0 ± 0.1	0.6 ± 0.1
Templeton loam	0.9 ± 0.2	0.8 ± 0.1
Wakanui clay loam	0.7 ± 0.1	> 0.8
Waimakariri loam	0.9 ± 0.1	1.0 ± 0.3

[A] Mean and standard error.

Conclusions

The intrinsic sorptivity repellency index (RI) showed that 14 New Zealand soils with a wide range of textures were water repellent (RI > 1.95) at field moisture conditions. It appears that water repellency is the norm rather than the exception, with the degree of water repellency variable. The RI is more sensitive than the Molarity of Ethanol Droplet (MED) and Water Drop Penetration Time (WDPT) tests for soil water repellency, and is therefore particularly useful for evaluating soils with low degrees of water repellency.

The RI has a number of other advantages over the MED and WDPT tests. The RI is a physically significant parameter which can be used to calculate actual and 'potential' short-time water infiltration. This may then be compared with rainfall and irrigation intensities. The RI may be measured *in situ* or on undisturbed cores at either field-moist or air-dry conditions. Elimination of macropore flow using a negative supply potential reduces the effect of disturbance when cores are used.

The distinction between 'critical' and 'sub-critical' water repellency drawn by Tillman *et al.* (1989) is not warranted, when the physical significance of 'sub-critical' repellency is examined. Soils which appear to wet normally may have water repellency of hydrological importance. King's (1981) MED severity scale should also be reviewed in light of this finding.

In all soils the I *vs* $t^{1/2}$ relationship was linear over sufficient time for the sorptivity of water and ethanol to be measured. At longer times the curve for water tended to increase with time in the more repellent soils, however the effect was not consistent. The slope of I *vs* $t^{1/2}$ for ethanol decreased with time for most soils. This was probably due to resident water pushed ahead of the ethanol.

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CHAPTER SIX: WATER REPELLENCY IN SPORTS TURF

6.0 INTRODUCTION

Repellency in sports turf has been the subject of few scientific studies and many anecdotal suppositions. Our primary interest in sports turf repellency developed from the work with wetting agents and close liason with the New Zealand Turf Culture Institute. The primary purpose of the research described in this chapter was twofold:

1. To evaluate the application and success of wetting agents for repellency control in golf greens;
2. To determine why repellency in golf greens is normally expressed in irregular, localised patches.

6.1 A STUDY OF WATER REPELLENCY IN NEW ZEALAND GOLF GREENS

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Abstract

Water repellency or 'dry patch' in New Zealand golf greens was found to be a major management problem, with two-thirds of 32 course superintendents surveyed reporting nine or more greens affected. Dry patch normally developed in the summer months, but persisted in some areas over dry winters. Superintendents found that the position of dry patch in a green was in some cases related to topography, but in other cases occurred irrespective of relief.

No significant difference ($p > 0.05$) was found in the water repellency of air-dried soil cores removed from dry patch and non-dry patch areas. There was also no significant difference ($p > 0.05$) in the thatch content between dry patch and non-dry patch areas. Thatch was found to be severely water repellent, and therefore contributed to water repellency. However, the soil alone from dry patch and non-dry patch areas was found to be severely repellent to 30 mm depth, and water repellency extended to 100 mm depth.

A correlation was found between dry patch areas and poor wetting from irrigation, using a simple 'catch can' test on a golf green. Therefore, it was concluded that although all areas of the greens evaluated have equal potential to develop water repellency, only the poorly irrigated areas developed dry patch symptoms. Only 14 of the course superintendents surveyed cited irrigation as a dry patch management factor.

Soil wetting agents were used by 95% of golf course superintendents to alleviate dry patch. The product 'Wettasoil' was used by 86% of superintendents at 10-20 l ha^{-1}, 1-3 times per year, and was found to be effective. Other cultural techniques cited by superintendents for dry patch management included coring, grooving, spiking and applications of lime or blood and bone.

INTRODUCTION

Water repellent soils are characterised by the way in which the solid phase interacts with water. Water repellent soils exhibit hydrophobic properties when dry, resisting water infiltration into the soil matrix (Brandt 1969a). Water repellency has long been recognised as a turf management problem (Letey *et al.* 1963). Bond (1978) used the term 'dry patch' to describe irregular areas of turf which suffer from moisture stress because the soil beneath the patch is water repellent and does not become uniformly wet after rain or irrigation. Turf death may occur despite what would seem adequate irrigation or rainfall (Wilkinson and Miller 1978), reducing the aesthetic and playing quality of the turf.

Dry patch is a common problem in numerous countries. In Britain, Shiels (1982) and Jones (1983) recorded the occurrence of dry patch on a number of golf greens following a series of dry summers. Danneberger and White (1988) noted that dry patch is prevalent on many golf courses throughout the cool-season turfgrass region of the United States of America. Charters (1980) reported that the dry patch condition was widespread in both the golf and bowling greens of Australia. Rankin and Ross (1982) reported that the problem was widespread in golf greens in the Wellington area of New Zealand.

A range of management techniques are used to ameliorate dry patch in sports turf. Soil wetting agents are surface active agents (surfactants) which increase the rate of water infiltration into water repellent soils (Mustafa 1969; Letey *et al.* 1962b). Wetting agents are widely used for sports turf, however New Zealand turf agronomists (Howard pers. comm.) have found that dry patches persist despite the application of products known to be effective (Wallis *et al.* 1990b). Tucker *et al.* (1990) found no correlation between dry patch severity and the use of wetting agents in a survey of golf greens in Georgia, U.S.A.

Coring (Bond 1978) and coring in conjunction with wetting agent application (Wilkinson and Miller 1978) have been found to alleviate dry patch. Control of thatch (partially decomposed plant material at the turf surface) may also alleviate dry patch since thatch is water repellent when dry (Wilkinson and Miller 1978). Wallis *et al.* (1990b) found that the irrigation regime affected plant growth in untreated and wetting-agent-treated water repellent sand.

Research was undertaken by the Department of Soil Science, Massey University in order to:

1. Identify the occurrence and severity of water repellency or 'dry patch' in New Zealand golf greens;
2. Establish the management practises utilised by golf course superintendents to control dry patch;
3. Attempt to identify the reason(s) for dry patch persistence despite the imposed management practises.

MATERIALS AND METHODS

A questionnaire survey of 42 golf course superintendents was conducted during the 1988/89 summer. In addition, soil samples were collected from 31 golf greens covering 9 golf clubs in the greater Auckland, Hawkes Bay and Christchurch areas. Soil cores 100 mm diameter by 200 mm deep were removed from dry patch and non-dry patch areas of greens using a hole cutter and transported intact to the laboratory. Each core was sliced into 10 mm deep sections and air dried.

Samples were evaluated for water repellency using the Molarity of Ethanol Droplet (MED) test, first proposed by Watson and Letey (1970) and developed by King (1981). The MED test measures the molarity of an aqueous ethanol droplet required for soil infiltration within 10 seconds. Ethanol lowers the liquid surface tension, enabling infiltration. King (1981) provided the following guidelines for interpretation of MED values: MED = 0, non-repellent; MED < 1, low repellency; MED 1.0 - 2.2, moderate

repellency; MED > 2.2, severe repellency.

MED was measured on the intact surface of each soil section (intact soil). The uppermost section (0-10 mm) of each core was then broken up by hand and the thatch separated from the mineral component with the aid of a 2 mm sieve. The proportion of thatch and soil in each core was measured by weight. Sub-samples of the soil only fractions were placed in petri dishes, lightly pressed down and measured by the MED test. A number of thatch samples were ground, pressed and also measured by the MED test.

To establish the relationship between the application of irrigation water and the development of dry patch, a sprinkler application uniformity test was conducted on the eleventh green of the Manawatu golf course in Palmerston North. 'Catch cans' were placed at regular intervals across the green, and after 30 minutes of irrigation the volume of water collected in each can was measured, and the sprinkler application rate and coefficient of uniformity calculated. The areas prone to dry patch development were then compared with the irrigation application rate.

To investigate how dry patch soil behaved when treated with a wetting agent and irrigated, a simple laboratory experiment was conducted. Two 0-10 mm core sections were selected with thatch contents of 4.9% and 15.2%. The wetting agent 'Wettasoil', which has been found to be effective at alleviating water repellency (Wallis *et al.* 1990b), was sprayed onto the surface of each core at 10 l ha^{-1} and 1:100 dilution. Five millimetres of 'irrigation' was then applied with a hand-held sprayer and the water distribution in the cores was visually assessed.

RESULTS AND DISCUSSION

(i) Occurrence of Dry Patch

Golf course superintendents were asked to rank dry patch as a management problem between 1 and 10, where 1 represented the most important management problem and 10 the least. One half of the superintendents ranked dry patch in the

top 3 of management problems (fig. 6.1). Of the superintendents who ranked dry patch < 3 as a management problem, 57% reported 'good' or 'very good' control of the problem with wetting agents. A number of others may have ranked the problem lowly because they managed courses in areas such as the Waikato with relatively high summer rainfall. Nonetheless, the dry patch problem was widespread. Two-thirds of courses had nine or more holes affected by dry patch.

Most superintendents (69%) felt that dry patch was a seasonal problem. This response was expected, since water repellency becomes most severe when soil is dry (Bond 1969a; Wallis *et al.* 1990a). Of interest were the 31% of superintendents who asserted that dry patch was non-seasonal or may be seasonal. Many of these superintendents managed golf courses in the eastern South Island, which suffered from a very dry winter in 1988.

Superintendents were equally divided in opinion when questioned whether dry patch was, was not or may be related to topography. On some greens, the soil sampling revealed that dry patch was most severe on higher areas of turf, yet on other greens dry patch was equally prevalent on lower and higher areas of turf.

(ii) Water Repellency of Dry Patch and Non-Dry Patch Areas

There was no significant difference ($p > 0.05$) in water repellency between dry patch and non-dry patch cores at all depths (fig. 6.2). Water repellency was severe (MED > 2.2) to 30 mm depth in dried samples from both dry patch and non-dry patch areas and on average all turf soil was water repellent to more than 100 mm depth. The reduction in repellency from 0 to 10 mm depth was significant ($p < 0.05$), which may have reflected higher organic matter contents in the surface soil. Wallis *et al.* (1990a) found that the MED profile of a water repellent sand was closely correlated with carbon content.

The soil core results suggest that, although only the 'dry patch' areas of the greens displayed obvious symptoms of water repellency, the remainder of the greens would become equally water repellent upon becoming dry. Tucker *et al.* (1990)

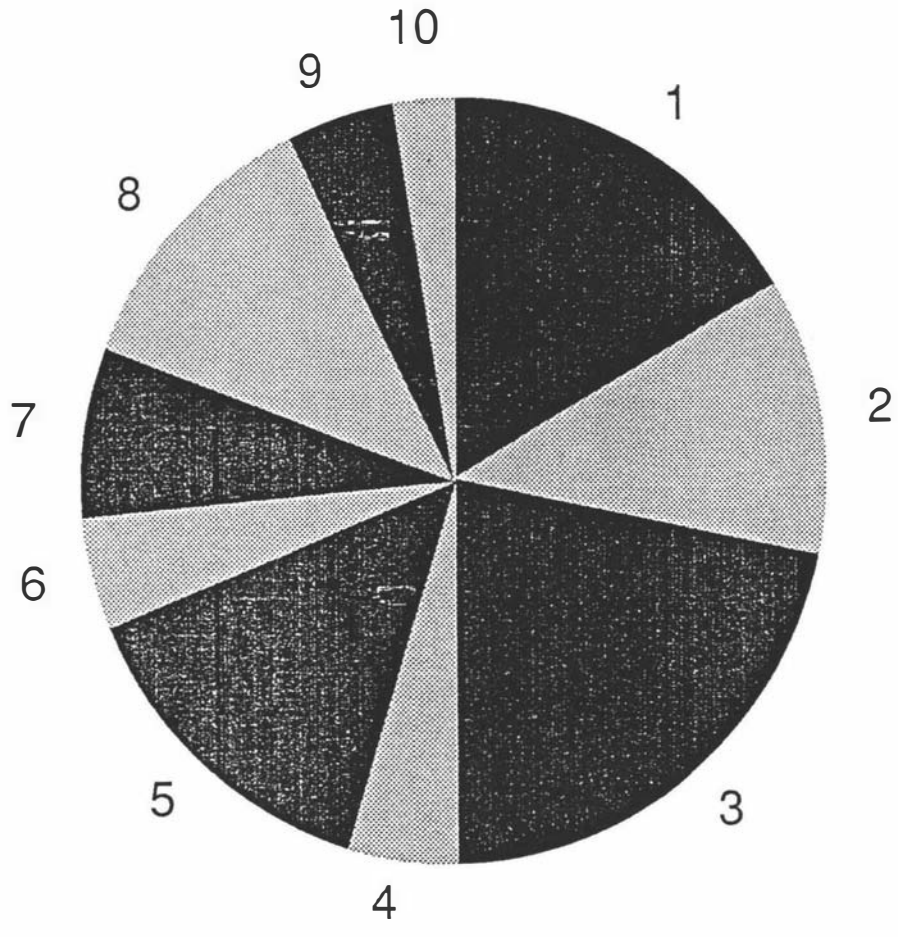


Figure 6.1. Ranking by 42 New Zealand golf course superintendents of dry patch as a management problem. (Ranking from 1-10, 1 = most important).

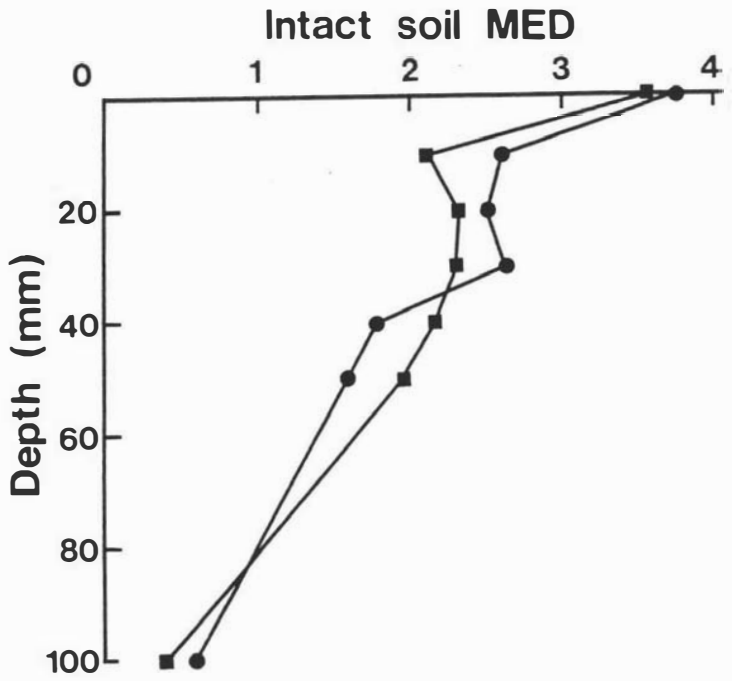


Figure 6.2. Soil water repellency (MED) profiles of dry patch (●) and non-dry patch (■) cores removed from 31 New Zealand golf greens (LSD(0.05) = 0.69).

found that the liquid-solid contact angle of oven-dried non-dry patch soil was very similar to that for dry patch soil. However, they found that the time for water drop penetration (WDPT) on field-moist dry patch samples was greater than the WDPT for non-dry patch soil. This finding was probably due to the higher moisture content of the non-dry patch soil, rather than an inherent difference in the soil water repellency. Contact angle (H) measurements on oven-dry soil by Tucker *et al.* (1990) showed that the dry patch soil was slightly more repellent than non-dry patch soil (dry patch mean $H = 86°$, non-dry patch mean $H = 74.7°$).

The differences in thatch content and soil-only MED between the dry patch and non-dry patch cores were not significant ($p > 0.05$) (Table 6.1). Since thatch is much lighter than the mineral fraction, 20% thatch content by weight represents a substantial proportion by volume. Dry thatch is known to reduce the rate of water infiltration (Taylor and Blake 1982). The ground thatch samples were severely water repellent, with MED values ranging from 2.6 to > 5.0. However, although thatch plays a major role in dry patch development, thatch is not a prerequisite for water repellency as the soil alone was severely water repellent. Wilkinson and Miller (1978) and Danneberger and White (1988) made similar observations. The soil-only MED values averaged 3.4 compared to the average intact soil MED of 3.7 (fig. 6.2).

Table 6.1 Thatch content and soil water repellency (MED) of 0-10 mm depth dry patch and non-dry patch samples removed from 31 New Zealand golf greens.

Soil core analysis	Dry patch area	Non-dry patch area	L.S.D. (0.05)
Thatch content (% by weight)	18.6	21.8	7.7
Soil-only MED	3.5	3.3	0.54

(iii) Dry patch formation

During the survey we observed that poorly irrigated greens (as a consequence of poor irrigation design and/or management) appeared to develop the most severe dry patch. The irrigation uniformity study on the Manawatu golf course identified that dry patch developed in the areas of the green which received the least amount of water (fig. 6.3). The dry patch areas were found at the base of the second tier in the green, where one would normally expect relatively moist conditions. This is in agreement with the previously noted observations that dry patch may develop in a green irrespective of topography. Way (1990) also found that dry patches developed on greens in areas receiving the least irrigation water. Tucker *et al.* (1990) found no relationship between dry patch severity and the use of increased irrigation, but did not investigate irrigation uniformity.

The irrigation system on Manawatu green 11 was found to have a coefficient of uniformity, C_u = 64%, with the application rate varying threefold across the green (fig. 6.3). Way (1990) found that many New Zealand golf courses had poor C_u values, with only 22% of C_u > 80%. Way pointed out that even when C_u was greater than 80%, it was still common to find a twofold variation in application rate. Constraints for irrigation designers, such as sprinkler head placement outside irregularly shaped greens, make 'uniform' sprinkler application difficult to achieve. However, recent advances in sprinkler head design may make more uniform water coverage possible (Way 1990).

Many of the course superintendents surveyed stated that they used frequent, light irrigations during the summer (typically daily applications of 5 mm water). The effect of this irrigation regime upon dry patch development was investigated in the laboratory using soil cores which were irrigated after wetting agent treatment. Most of the applied water was retained within the surface 10 mm. This would encourage shallow turf rooting and increase the risk of plant stress in hot, dry conditions or when other plant stress factors develop. In one of the soil cores examined water was observed to move preferentially down through a recently created core-hole. It would appear that the sand within the core hole had not (as

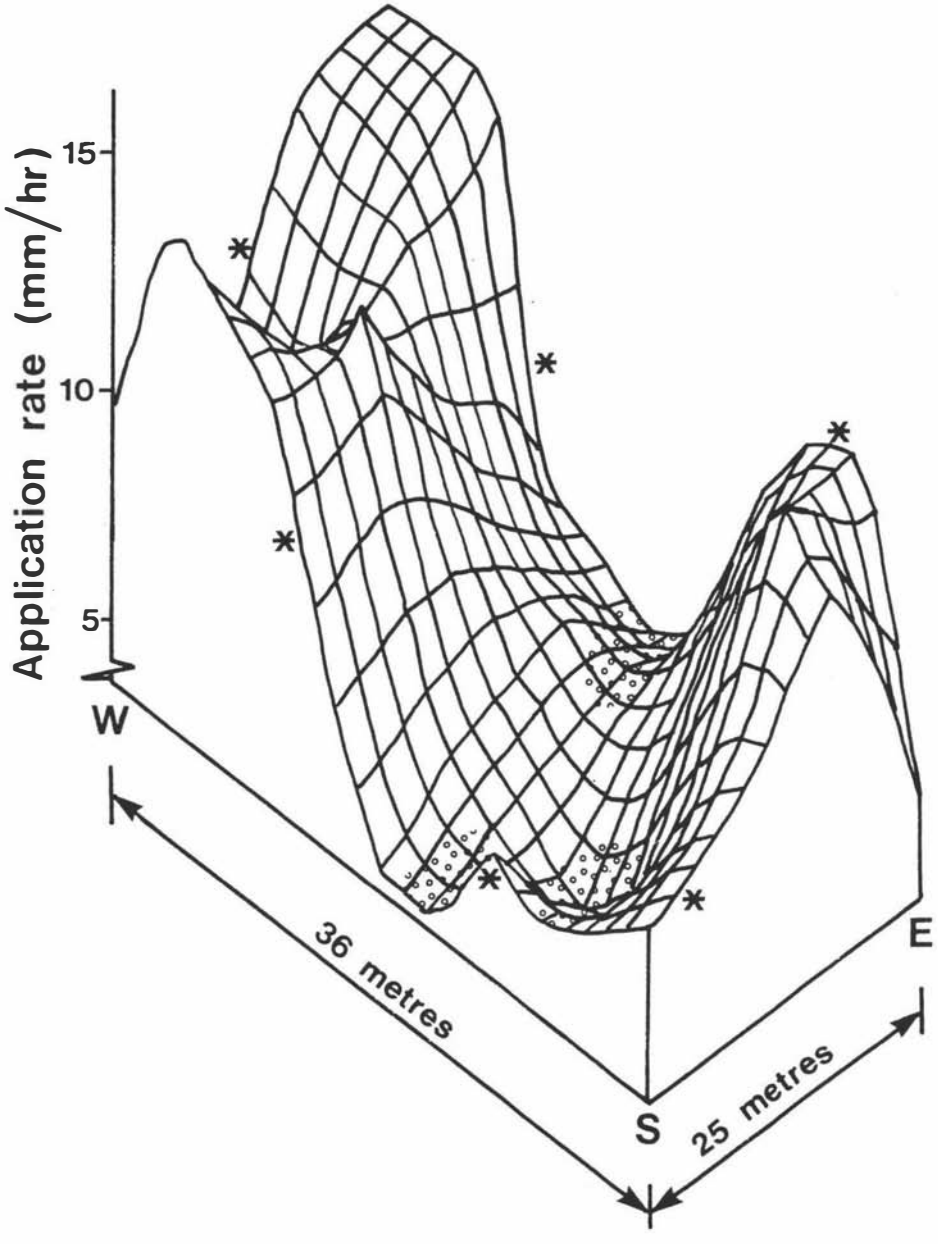


Figure 6.3. Contour map of the irrigation application rate on green 11, Manawatu golf course, Palmerston North, New Zealand. Shaded zones represent dry patch areas. Positions of sprinkler heads are indicated (*).

yet) developed a water repellent coating. This observation supports the finding of Bond (1978), that coring is effective for dry patch alleviation.

(iv) Techniques used to alleviate dry patch

Nearly all superintendents (95%) used wetting agents to alleviate dry patch. Most superintendents (86%) used 'Wettasoil', a product which Wallis *et al.* (1990b) found compared favourably to other products available on the New Zealand market. Of the superintendents using Wettasoil, approximately 70% evaluated the performance of the product as 'good' or 'very good'. This ranking was relative to the performance of other wetting agents, as most superintendents spoken to said that they had used other products.

The Wettasoil application rates used by superintendents varied. Few superintendents used rates below 10 l ha^{-1} or above 60 l ha^{-1}, nearly 50% applied Wettasoil at 10 to 20 l ha^{-1}. Wallis *et al.* (1990b) found that, with the aid of correct irrigation management, Wettasoil was effective at rates less than 10 l ha^{-1} on a naturally occurring, severely repellent sand (MED = 2.6). The rate needed for a particular golf green would be expected to be site specific, and could be determined by field evaluation or glasshouse experiments. Field evaluation would be preferable, since the effects of the natural environment (climate, irrigation regime, thatch etc.) are expressed in the results.

The number of annual Wettasoil applications used on greens ranged from 1 to 6, with most superintendents using between 1 and 3 applications per year. The first application was often a blanket cover applied in spring or early summer. Strategic applications (spot sprays) were then used during the summer as dry patches became noticeable. Many superintendents expressed the need to get the first spray on early, well before dry patch symptoms develop. This has also been the experience of New Zealand Turf Culture Institute consultants (Howard, pers. comm.) and British research (Baldwin 1990).

The application rates and number of annual applications can be used to determine the total annual application of Wettasoil. Most superintendents used 20-40 l ha^{-1} of Wettasoil each year, with 23% using 40-60 l ha^{-1} yr^{-1} and 27% using over 60 l ha^{-1} yr^{-1}. The 'total' application was often restricted to those areas which received spot sprays in summer. For example, the whole green may receive 20 l ha^{-1}, but some areas may receive over 60 l ha^{-1}.

Low dilution rates (concentrated solutions) were most often used for Wettasoil application. Over 60% of superintendents used dilution rates below 1:100. One practical reason for selecting a low dilution rate is to minimise the volume (and weight) of solution that must be applied to the greens. Wallis *et al.* (1990b) found that Wettasoil at a dilution rate of 1:100 was no less effective than at dilution rates of up to 1:1000. However, low dilution rates increase the danger of wetting agent phytotoxicity (Effron *et al.* 1990). They noted that the risk of phytotoxicity may be minimised by avoiding application on hot, sunny days and by following application with immediate irrigation.

Inefficient irrigation impacts upon dry patch development and has implications for the use of wetting agents for dry patch control. There is little benefit to be gained by repeated, large applications of wetting agents if areas of the turf remain inadequately irrigated. A number of course superintendents we surveyed had managed to overcome the dry patch problem, despite having poor irrigation systems, by employing regular hand-watering of poorly irrigated areas of greens known to have dry patch potential. This approach was labour intensive, but was judged worthwhile compared with the high capital cost of installing a new or improved irrigation system.

Only fourteen of the superintendents surveyed cited irrigation as a key factor in dry patch management. This is of some concern in light of the trial results described above. A prudent recommendation would be to schedule irrigation carefully, using regular observation of soil cores or scheduling devices such as tensiometers. Way (1990) found that no superintendent he surveyed used a quantitative irrigation scheduling technique, suggesting that there is scope for

improved irrigation management. A regular deep watering should be used (perhaps once a week) to prevent the soil from excessive drying and to maintain an adequate root depth. Deep watering following wetting agent application would be expected to be particularly beneficial.

Superintendents surveyed cited the use of a range of cultural techniques, other than wetting agent application, for dry patch management. Coring was being used as a dry patch management tool by 16 superintendents. Coring was shown by Bond (1978) to alleviate dry patch most effectively when the cores were backfilled with sandy loam. Wilkinson and Miller (1978) and Danneberger and White (1988) have found that wetting agent application in conjunction with coring was more effective than coring alone. Spiking was less frequently used (7 superintendents), and grooving to reduce thatch was cited as a dry patch management technique by 4 superintendents.

Applications of lime and blood and bone were cited by 3 and 5 superintendents respectively for dry patch alleviation. Although the effects of these products upon turf water repellency have not been investigated, it is hypothesised that liming and organic fertilisers may stimulate biological breakdown of the hydrophobic organic coating surrounding water repellent soil particles.

Jackson and Gillingham (1985) found that liming reduced the water repellency and increased the moisture content of six New Zealand agricultural soils. The effect was most marked in late summer or early autumn following dry periods. In a field experiment in which plots were limed and then irrigated, they found that liming produced an immediate 3% increase in soil moisture compared to unlimed plots. This effect was too rapid to be accounted for by soil structural changes facilitated by soil microorganisms.

CONCLUSIONS

Water repellency or dry patch was found to be a major turf management problem in New Zealand golf courses. No significant difference was found between the water repellency and thatch content of air-dried samples from dry patch and non-dry patch areas of greens. The inadequately irrigated areas of a green developed dry patch symptoms, which would be expected to persist regardless of wetting agent applications.

ACKNOWLEDGEMENTS

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CHAPTER SEVEN: GENERAL DISCUSSION AND CONCLUSIONS

Water repellency is generally regarded as an uncommon exception to 'normal' soil behaviour. Although severe repellency may not be common in natural soils, it would appear that large areas in New Zealand may be affected by the problem, ranging from coastal yellow-brown sands to hill country pasture (Beaver and Valentine pers. comm. 1991). The occurrence of repellency in natural soils will remain unknown until a wide-scale survey is conducted or until repellency measurements become standard field suveying practise. Despite their limitations, the relatively simple WDPT and MED techniques would be most suited for surveying.

Heat-induced repellency has received little attention in New Zealand, and has been beyond the scope of this research. Recently Basher *et al.* (1990) suggested that repellency research should be a priority for investigations into the effects of burning in New Zealand. They pointed out that repellency may contribute to overland flow, erosion, and problems for plant recovery and succession.

Severe repellency was found to be the rule rather than the exception in New Zealand golf greens, and could not be attributed solely to thatch. Repellency may also be widespread in other types of sports turf, particularly those in which sand is used for construction and/or textural amendment.

Development of the intrinsic sorptivity repellency index has provided an improvement over existing measurement techniques because it is both sensitive and physically meaningful. Repellency affected the rate of infiltration into all the soils measured, which has led to the suggestion that all soils are repellent to some degree. Furthermore, it was found that slight degrees of repellency in soils which appear to absorb water normally can be hydrologically significant. Such innocuous repellency may well affect many soils and could be a neglected factor in the consideration of and modelling of soil water dynamics.

The extreme spatial variability of repellency is both difficult to explain and frustrating for field research. Geostatistics enabled quantification of repellency variability by inference

from the soil water content, which was rapidly and conveniently measured with the time domain reflectometer. Although geostatistics proved illuminating, it was shown to have a number of limitations when analysing water content in a repellent sand. This criticism notwithstanding, geostatistics indicated the effect of repellency upon soil water movement in different seasons, under irrigation, and under irrigation after application of wetting agent.

Geostatistical analysis indicated that at the Himatangi site, rainfall and irrigation water infiltrates into less repellent areas or zones. The size of these zones, indicated by the range of spatial dependence, change with time. In winter when rainfall is persistent and the water table is within c. 1 m of the surface, the zones are relatively large and surface soil water contents are relatively uniform. By comparison, in summer when the soil dries and begins to exhibit repellency, the zones of relatively less repellent soil into which water may infiltrate contract in size. This gives rise to the extreme variability in moisture content associated with repellent soil. The relatively large nugget variances in summer substantiate high spatial variability of water content over small distances, within the larger zones of spatial dependence indicated by the variograms.

The manner in which repellency develops is very complex. The study of yellow-brown sands yielded a number of remarkable findings, such as the rapid development of the most severe repellency in the youngest soil with the least organic matter, and the subsequent decline in repellency with increasing soil age. Also, the simple relationship between repellency severity and % organic carbon first identified in the Himatangi sand profile did not hold for other soils of the development sequence. The composition of the organic matter which produces hydrophobic coatings on soil particles is more important than the quantity of organic matter *per se*. The variable nature of repellency indicates that only specific plants and/or soil microorganisms have played key roles in repellency development. Identifying the plants and microorganisms responsible for repellency in New Zealand was beyond the scope of this study.

The organic matter extracted from the yellow-brown sands with *iso*-propanol/ammonia had remarkable similarities with that previously extracted from repellent soils by other researchers, particularly by Ma'shum *et al.* (1988). Further elucidation of the specific

compounds involved is required, and it is hoped that ongoing research will establish a correlation between the concentration of such compound(s) and repellency severity.

In this study a number of factors influencing the performance of wetting agents have been evaluated, including the importance of the irrigation regime. In the glasshouse studies, the wetting agent most used by golf superintendents (Wettasoil) was effective at low application rates. However, despite the fact that superintendents commonly applied higher application rates to turf with repellency severity comparable to that of the soil used in the glasshouse studies, dry patches persisted. When it was found that the entire greens had equal repellency severity when dry, the link between poor irrigation, low soil water content and subsequent repellency expression became clear. A recent study has found that the application uniformity of most sports turf irrigation systems in New Zealand is poor. Improvements in irrigation design and management would enable greater dry patch control and alleviate many other problems related to turf stress from drought or waterlogging.

Although wetting agents and irrigation are important for repellency control in sports turf, their use in many enterprises is restricted by economics. Reduction of repellency by soil agitation indicated that cultivation could be a viable field treatment, however the success of cultivation would be dependent upon the depth and severity of the repellent horizon and the amount of physical abrasion and soil mixing produced. A further problem is that any mitigation of repellency may be short-lived. Longer-term control may be achieved by amendment of soil texture, but its application is also restricted by practical and economic concerns. Complete control of repellency may be elusive until repellency development is fully understood.

The field of repellency research is both demanding and rewarding. Demanding, because although the thrust of this research has been from a soil physics perspective, understanding the problem has necessitated consideration of soil biology, organic chemistry and botany. Rewarding, because there are many opportunities for discovery. A list of future research priorities is given in chapter one. The most significant advancements are likely to arise from a well-coordinated, multidisciplinary approach.

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